The Corrections for Significant Waveheight and Attitude Effects in the TOPEX Radar Altimeter

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ABSTRACT

The routine ground processing of the data from the NASA radar altimeter of the TOPEX/POSEIDON mission includes corrections for the effects of significant waveheight and attitude angle changes on the altimeter's estimates of range, backscattered power, and significant waveheight. This paper describes how the corrections were generated and how they are applied. Detailed waveform fitting to telemetered waveform samples is used to assess the effectiveness of the corrections. There are several altimeter hardware-caused small waveform departures from the model waveforms, and these waveform features are described in detail. The results and discussion are restricted to Side A of the redundant altimeter.

INTRODUCTION

For the NASA radar altimeter of the TOPEX/POSEIDON mission (referred to hereafter as the TOPEX altimeter), we report on corrections of range estimates for the effects of ocean significant waveheight (SWH) and satellite attitude (off-nadir) angle. In general, a radar altimeter's on-board estimation of range will be limited by on-board computational capability and by time constraints; for example, the TOPEX altimeter's range estimate must be formed within the range update interval of about 0.05 seconds. The ground data processing will correct the altimeter's estimates of range and also of backscattering cross-section (σ^0) and significant waveheight SWH. The corrections are functions of the SWH and of the attitude angle. In earlier radar altimeters the corrections for SWH and attitude effects were implemented as a set of look-up tables. For the TOPEX altimeter processing, these corrections are performed by sets of polynomials. This paper describes briefly our TOPEX altimeter simulations which provided the initial values for the coefficients in the correction polynomials. Detailed waveform fitting to telemetered waveform samples has been used to assess the effectiveness of the corrections. We will concentrate our discussion on the Ku-band corrections for the TOPEX altimeter.

After TOPEX/POSEIDON was launched, we found a number of small waveform departures from the model waveforms. Because we expect that other investigators will be interested in waveform fitting to TOPEX altimeter data, we have attempted to describe the features in some detail. These waveform features were incorporated into further simulation which supplied the updated correction coefficients now in place in the TOPEX altimeter's production ground processing.

Both the TOPEX altimeter tracker simulations and the waveform fitting of on-orbit data use the same model waveform which is briefly reviewed. The waveform features are described. Some of these features vary with the magnitude of the fine height word within the on-board altimeter tracker, so the digital filter bank (DFB) is also discussed. A set of corrections has been developed to correct the telemetered waveform samples, in an average sense, for the waveform features.

The TOPEX altimeter is a redundant system which has two separate sides, designated Side A and Side B. Only Side A has been operated in flight, and this paper's results and discussion are restricted to Side A.

CORRECTION ALGORITHMS

Algorithm Development Process

Because the TOPEX Project was aimed at the highest accuracy data for science uses, it was decided that there should be a thorough algorithm development process with participation by members of the Science Working Team. The accuracy desired from all algorithms was a few millimeters so as not to add significantly to the altimeter noise of about 2 cm.

Algorithm developers wrote prototype code for many of the algorithms. The prototype code was also assembled, with early parts of the science processing system, into a complete prototype processing system. This system allowed the generation of a complete test GDR from instrument test data. Prototype system output at several stages was used during testing of the final science processing system. The prototype was also used during mission operations for quick look data processing and for testing updated instrument constants.

Algorithms Correcting for Effects of SWH and Attitude

The TOPEX altimeter, described more fully by *Zieger et al.* [1991] and *Marth et al.* [1993], has 128 on-board waveform samplers. These samplers are combined (averaged) in multiples of 1, 2, and 4 to form the 64 telemetry samples available in normal track mode, as summarized by Table 1. For this paper we will only use the term waveform samples to refer to members of the on-board set of 128 samplers; the samples available in the data stream and in the ground data processing will always be referred to as telemetry samples. There are also several waveform gates formed within the altimeter, where the term "gate" is used to designate the average of a specified range of on-board waveform samples.

The TOPEX altimeter has five different sets of tracking gates, each set consisting of an Early, a Middle, and a Late gate. Each set is designated by a *gate selection index,* to be called igt in this paper. See *Zieger et al.* [1991] for a fuller review of the tracking gates. The narrowest tracking gates are at the gate selection index igt of 1, the widest at igt of 5, and the altimeter is allowed to change values of igt only at data frame boundaries (approximately 1 second). Because of this adaptive resolution the correction algorithms must treat the Ku-band altimeter as five separate altimeters, one for each igt value. The same *form* of correction will be applied but the correction coefficients will be different for each igt value. Similarly, the C-320 and the C-100 must each be regarded as five separate altimeters.

Early in the algorithm development process we decided that corrections for attitude effects would be based on the Ku-band altimeter waveforms rather than on output from the spacecraft's attitude control system. Jointly with the TOPEX Project, it was decided that the corrections were to be produced for a SWH range 0 to 20 meters and for an attitude range of 0 .0 to 0.45 degrees. After a number of simulation studies, we decided that adequate corrections for the TOPEX altimeter's data frame (approximately 1 second) would be based on waveform data from within that frame only. Initial values for the corrections would be based on pre-launch simulation studies, and the corrections would be "fine-tuned" by the results of model waveform fitting to over-ocean data during the Verification Phase (the first 6 months) of the TOPEX/POSEIDON mission.

Functional Form for Corrections

Our various simulation studies indicated that the TOPEX Ku-band altimeter range corrections for effects of SWH and attitude could be expressed as a general polynomial form in two parameters to be described later in this paper: i) the SWH-related quantity, V_{SWH}; and ii) the attitude-related quantity V_{ATT}. The general polynomial form of the corrections is:

$$\begin{aligned} \mathrm{Corr} &= a_1 + a_2 \times V_{SWH} + a_3 \times V_{ATT} \\ &+ a_4 \times V_{SWH}^2 + a_5 \times V_{SWH} \times V_{ATT} + a_6 \times V_{ATT}^2 \\ &+ a_7 * V_{SWH}^3 + a_8 \times V_{SWH}^2 \times V_{ATT} + a_9 \times V_{SWH} \times V_{ATT}^2 + a_{10} \times V_{ATT}^3 . \end{aligned}$$

For the TOPEX Ku-band altimeter range correction there will be one set of coefficients, a_1 to a_{10}, for each of the five igt values for each altimeter. The final Ku-band SWH estimate is also expressed by the same polynomial form in V_{SWH} and V_{ATT} (with of course a different set of coefficients). For the Ku-band AGC corrections the first six coefficients in the above general form are adequate (*i.e.*, terms only through V_{SWH}^2, $V_{SWH} \times V_{ATT}$, and V_{ATT}^2). The C-band altimeter corrections were initially generated for same polynomial forms as the Ku-band corrections, but the C-band dependence on V_{ATT} is much less because of the wider antenna beamwidth for the C-band altimeter.

COMPUTATIONAL DETAILS

Model Waveform

It is assumed that the concept of the "effective" pulse (in the time domain) can be used, ignoring actual details of the pulse compression scheme. (See *Chelton et al.* [1989], for a useful discussion of pulse compression.) Then as shown by *Brown* [1977] the altimeter mean return waveform W(t) is given by the convolution

$$W(t) = P_{FS}(t) \otimes q_s(t) \otimes p_\tau(t) ,$$

where $P_{FS}(t)$ is the flat-sea impulse response function, $q_s(t)$ is the radar-observed surface elevation probability density function (p.d.f.), and $p_\tau(t)$ is the radar altimeter's point-target response function.

The flat-sea impulse response function $P_{FS}(t)$ from *Brown* [1977] (as modified by *Rodriguez* [1988] for Earth curvature effects) includes radar antenna beamwidth and pointing angle effects. This $P_{FS}(t)$ assumes that the antenna gain can be represented by a Gaussian function of angle relative to the antenna axis. In our simulation and our waveform fitting, we use 1.08 degrees for the TOPEX Ku-band altimeter's antenna beamwidth after correcting the "plateau excess" described in the waveform features section. This beamwidth is 4% larger than the preflight antenna range measurement of 1.04 degrees, but does lead to fitted attitude angles consistent with those from the spacecraft attitude control system in a series of attitude bias calibration maneuvers (ABCALs). (*Callahan and Haub* [1994] present further discussion of TOPEX altimeter's antenna pattern, and an argument for a somewhat different beamwidth.)

The radar-observed ocean surface elevation p.d.f. $q_s(t)$ is assumed to be a skewed Gaussian given by

$$q_s(t) = [(2\pi)^{1/2} \sigma_s]^{-1} \{1 + (\lambda_s/6)[(t/\sigma_s)^3 - 3(t/\sigma_s)]\} \exp[-(t/\sigma_s)^2/2] ,$$

where σ_s is the sea surface rms elevation, and λ_s is the surface skewness. All satellite altimeter estimates of significant waveheight assume that SWH is four times the rms surface elevation σ_s. The TOPEX altimeter algorithms were developed assuming the value 0.1 for λ_s, and our TOPEX altimeter waveform fitting work has also assumed this same fixed value. We feel that the small waveshape features from the TOPEX altimeter's digital filter bank (described later) jeopardize attempts to make reasonable skewness estimates from the TOPEX altimeter waveform data.

For the point-target response $p_\tau(t)$, we use the main lobe and first eight sidelobes of an assumed sinc^2 point-target response function with a 3.125 ns width. We had intended directly using data from preflight testing for the sampled shape of the point-target response, but the measurements were difficult and seemed to show secondary echoes from multipath problems believed to be an artifact of the test method. The experimental data do justify the use of the sinc^2 model function.

In both our simulation and fitting work the time quantization was one eighth of the 3.125 ns waveform sample separation. The model waveform has six parameters: a) overall amplitude scaling term; b) a range term expressing the location of the waveform's zero relative to the TOPEX altimeter's telemetry sample 24.5 (on-board waveform sample 32.5); c) the surface significant waveheight (SWH); d) overall signal baseline; e) the surface skewness λ_s; and f) the attitude angle.

Wallops TOPEX Altimeter Simulation Program WALTOPEX

During the TOPEX development, we wrote a Fortran program WALTOPEX to simulate the action of the TOPEX altimeter's track loop for the expected over-ocean model waveform. The TOPEX altimeter's on-board tracker is controlled by a (ground selectable) set of parameters and WALTOPEX is controlled by the same parameters, allowing us to examine consequences of changes in the flight parameters. WALTOPEX includes possible waveform additive and multiplicative adjustment factors, applied to the basic 128 waveform sample set. As the various waveform features were identified and their size estimated, we used the multiplicative and additive factors to build the features into the waveform and then assess tracker consequences of the waveform features.

The TOPEX altimeter's range tracker has five different sets of tracking gates, and chooses among these by a SWH-related algorithm. The gate index, igt, specifies which of the five sets of gates is used. WALTOPEX can choose its own igt, or can be forced to run with a single specified igt value. Realistic noise (usually referred to as Rayleigh or fading noise) can be included in the simulated waveforms into WALTOPEX, or the model waveform can be noise-free (in effect, the mean of an infinite number of individual returns). We have verified that if the waveform parameters are constant, the WALTOPEX output for noise-free waveforms (after waiting for start-up transients to disappear from the output) is the set of values to which the noisy waveform WALTOPEX record will converge in the mean. Comparing the WALTOPEX output to the input waveform parameters allowed estimation of the range bias for the particular specified SWH and attitude values.

For a given set of waveform features, first WALTOPEX was executed for a set of values spanning the entire correction space of 0 to 20 meters SWH and 0 to 0.45 degrees attitude to find the subregions of this space covered by each of the five possible values of gate index (igt). Then for each of the five igt values the following process was carried out: a) value SWH_{low} was chosen as the igt's lower SWH minus about 5% of the igt's SWH range; b) value SWH_{high} was set to about 5% above the igt's upper SWH; c) a set of 10 individual SWH values was chosen, uniformly spanning the range from SWH_{low} to SWH_{high}; d) for each of the ten SWH values, WALTOPEX was run for a set of 10 attitude values from 0.0 to 0.45 degrees; e) the resulting 100 WALTOPEX output values (10 SWH values times 10 attitude values) were used to find the ten coefficients for range correction, ten coefficients for SWH correction, and six coefficients for AGC correction.

TOPEX Waveform Fitting Program FITTOPEX

FITTOPEX is the TOPEX-specific version of our general iterative least-squares waveform fitting procedure used in earlier Seasat and Geosat work. FITTOPEX varies the model waveform parameters to obtain a minimum sum of the squares of differences between the model waveform and the input (corrected) telemetry samples, using the model waveform function already described. The function being fitted is not analytic, so the derivatives required in the fit procedure must be estimated numerically.

FITTOPEX operates on the 64 telemetry samples from the TOPEX altimeter. Both additive and multiplicative corrections can be applied to these samples. Different weights can be applied to each telemetry sample, but in this work we used only weights 1 or 0. Any combination of the six model waveform parameters can be set to constant values and the rest of the parameters fitted. In the work reported here, we used a fixed skewness value of 0.1 and fitted the five remaining waveform parameters. Zero weights were assigned to telemetry samples 1 to 4, 45 to 50, and 61 to 64, and unit weights were assigned to the rest of the telemetry samples. The zero weights were used to avoid filter bank end effects and leakages described later.

CORRECTIONS FROM WALTOPEX SIMULATION

Corrections as Function of SWH and Attitude

Figure 1 shows the TOPEX Ku-band altimeter's range corrections as a function of SWH for several attitude values from 0.0 to 0.4 degrees, produced from the WALTOPEX simulation program. Dotted lines were added to emphasize the separation into the five regions of different gate selection index igt. The range corrections can also be expressed as functions of a SWH-related parameter V_{SWH} and an attitude-related parameter V_{ATT}. The V_{SWH} is formed within the TOPEX altimeter while the V_{ATT} is formed in ground processing from waveform telemetry samples. The WALTOPEX program produces simulated V_{SWH} and V_{ATT} values.

V_{SWH} and V_{ATT} description

The significant-waveheight-related ratio V_{SWH} is formed within the TOPEX altimeter's range tracker as part of its selection of the gate selection index igt; see *Zieger et al.* [1991] for a description. In Seasat and Geosat the SWH estimate was produced from a V_{SWH} by on-board table look-up, and the table value of SWH was placed in the telemetry stream. The TOPEX altimeter instead places the V_{SWH} in the telemetry stream, and the table look-up is performed in the ground data processing.

In the TOPEX altimeter ground processing the attitude-related quantity V_{ATT} is formed from combinations of the scaled and corrected telemetry samples. Three gates are defined: the early gate G_{egt} is the average of telemetry samples 5 through 8; the AGC gate G_{agc} is the average of telemetry samples 12 through 37 for the Ku-band altimeter (telemetry samples 15 through 40 for the C-band altimeter); and the attitude gate G_{att} is the average of telemetry samples 57 through 60. Then a ratio V_{ATT} is defined by

$$V_{ATT} = (G_{att} - G_{egt}) / (G_{agc} - G_{egt}).$$

The V_{ATT} is dimensionless, but is sometimes referred to as an attitude-related voltage for historical reasons. For the TOPEX altimeter corrections in the ground processing, 1-frame averages of the V_{SWH} and V_{ATT} are used.

WAVEFORM FEATURES

We use the term "waveform feature" to denote a departure from the model waveform which is caused by the altimeter itself, and this section describes our current understanding of TOPEX altimeter's waveform features. All radar altimeters exhibit some waveform sample-to-sample variations, and the TOPEX altimeter's Calibration Mode 2 (CAL2) was designed to provide experimental data with which to correct or compensate for these variations. In CAL2, the altimeter is presented an effectively uniform (noise only) signal input and the fine-height word is swept through its entire range in about one minute.

As TOPEX altimeter's on-orbit data became available, we found that waveform fitting to CAL2-corrected telemetry samples revealed distinct patterns in the fit residuals. If the CAL2 corrections had been perfect, the residuals would have been randomly distributed about zero. There had been extensive preflight TOPEX altimeter testing using the RASE (the radar altimeter system evaluator which is, in effect, an "inverse altimeter"; see *Marth et al.* [1993]) but because of the difficulties in building the RASE and in matching its bandpass characteristics to the flight altimeter, some of the waveform features had not been seen nor their consequences understood until after launch.

Further laboratory measurements performed on the TOPEX altimeter engineering model in a 9-month period after launch showed waveform effects correlatable with the on-orbit observations. The problematic effects appear to arise from details of the TOPEX altimeter's digital filter bank (DFB). Some of the features are a function of the altimeter's fine-height word. In this section we will briefly review DFB details, will describe features not dependent on fine-height, and then will describe the fine-height-dependent features. The DFB is common to both the Ku-band and the C-band altimeters, and the waveform features also are common to both Ku and C. Sets of multiplicative and additive waveform corrections have been developed to compensate on average for the waveform departures from ideal.

Digital Filter Bank (DFB)

The digital filter bank (DFB) lies at the heart of the altimeter and its range tracking loop. More details are available in *Marth et al.* [1993], *Zieger et al.* [1991], and *MacArthur and Brown* [1984]. The transmitted pulse (320 MHz chirp bandwidth, 102.4 μsec pulsewidth, from the digital chirp generator) scatters off the ocean surface; the received return signal is dechirped, then mixed down to in-phase (I) and quadrature (Q) signals, filtered with a 625 kHz lowpass filter (the "anti-aliasing filter"), and digitized at a 1.25 MHz sample rate. At 1.25 MHz, the 102.4 μsec pulse results in 128 complex samples upon which the DFB performs a 128-point fast Fourier transform (FFT). The FFT output is 128 individual waveform samples, spaced effectively 9.765 kHz in frequency (equivalent to 3.125 ns time domain spacing), which are tracked by the adaptive tracker unit. The tracking error in the tracking loop is nulled by frequency shifting. The frequency shift, controlled by the track loop, is accomplished by applying a phase rotation algorithm to the I and Q samples just before the FFT is performed. The phase rotation rate is controlled by the tracking loop's fine-height word. A phase ramp across the uncompressed 102.4 μsec pulse has the effect of shifting the entire bank of 128 waveform samples. For example, a phase change of 2π across the pulse produces an equivalent compressed pulse sample shift of 3.125 ns. The total time adjustment by the phase shift method is 25 ns, and the TOPEX altimeter's fine-height word contains the range equivalent of this 0 to 25 ns. The total range timing is controlled by the phase shift and by varying the position of the chirp pulse in 12.5 ns steps which are reported by the TOPEX altimeter's coarse-height word(s). The 128 individual waveform samples are also combined (averaged) into the 64 samples that are placed into the telemetry to the ground. In this discussion the waveform samples will be numbered 1 through 128, and the telemetry samples will be numbered 1 through 64. The waveform-to-telemetry averaging depends upon altimeter mode, as summarized in Table 1. The DFB performs the same operations for both the Ku-band and the C-band altimeters.

In radar altimeters prior to TOPEX, the DFB's used the discrete Fourier transform with a maximum of 64 samples. For the TOPEX altimeter, the FFT was implemented in digital electronics to lessen the time required to perform the full transform for the 128 samples. In a perfect DFB, the output would be a perfect Fourier transform of the input with no extraneous effects being introduced by the DFB itself. The shape of the transformed pulse in amplitude versus frequency would look exactly like the time domain average return from a 3.125 ns transmitted pulse. But the TOPEX altimeter DFB does not provide a completely perfect transform, and there are several small effects of the DFB hardware/software on the shape of the output.

DFB Effects Not Depending on Fine-Height Word

Zero leakage: At the center of the filter bank (waveform sample 65 out of the full 128) there appears to be an excess signal, spread across several samples. Waveform sample 65 is the zero-frequency sample. This zero-frequency leakage appears to be present in all the TOPEX altimeter filter banks tested (*i.e.*, engineering model, breadboard unit, and both Side A and Side B in the flight unit), and is seen in all modes (Standby, Calibration, and Tracking). The zero-frequency leakage is not affected by AGC or receiver gain, and appears to be an additive effect only. The probable explanation for this was found by a tracker simulation which included specific details of the mathematics performed in the on-board digital FFT; it was found that there was a right shift-caused truncation in the DFB where round-off should have been used, and when the right shift is corrected in the DFB simulation the zero leakage disappears [J.R. Jensen, private communication]. There is a subtle fine-height dependence in that round-off error will go to zero when the fine height is exactly zero with respect to any filter. Since in general the fine height is continually changing, the zero-leakage from round-off error will disappear only a small fraction of the time.

There may also be another dc or zero-frequency leakage from charge retained on the biasing capacitors in the analog to digital conversion; residual charge will act as a dc bias and therefore appear at the zero-frequency filter and its immediate neighbors.

FFT finite word length effects: The TOPEX altimeter's FFT word length is 8 bits (a limit set by device availability at the time of the altimeter design), and the DFB output exhibits "sawteeth" and a "plateau excess". The detailed DFB simulation included the effects of the finite word length (8 bits) FFT devices in the DFB. The simulation was able to demonstrate both sawteeth and plateau excess nearly matching what was being seen in TOPEX altimeter data. While these effects can generally be removed (or compensated for) in ground processing, they are present in the waveforms presented to the TOPEX altimeter's on-board tracker.

Sawteeth: The waveform samples exhibit an alternating up-and-down neighbor-to-neighbor variation. This effect is also cyclic in groups of eight samples, so that within each group of eight neighboring samples there will be one which is noticeably lower than the rest. The sawteeth are smoothed by the averaging from waveform to telemetry samples, so that in fine-tracking the sawteeth are seen only in waveform samples number 17 to 48 (available 1:1 as telemetry samples 9 to 32). The sawteeth are easier to see in CAL2 waveforms than in the fine-track data, because in CAL2 the signal on which the sawteeth ride is an approximately straight horizontal line. Figure 2 shows the sawteeth in typical Ku-band fine-track telemetry samples averaged for 5 seconds, and Figure 3 shows the sawteeth in CAL2. The sawteeth seem to be multiplicative, do not exhibit much variation with fine height, and in ground processing can be removed from telemetry samples by using multiplicative compensation factors derived from CAL2 data.

Plateau excess: Model TOPEX altimeter waveforms were generated at WFF for 2 meter SWH and attitude values of 0.0, 0.2 and 0.4 degrees: A set of values was generated for (internal) waveform samples 1 to 128, uniformly spaced at 3.125 n, with their track-point at sample 32.5, and having a (noise) baseline of zero. These model waveforms were used as input to the detailed DFB simulation, and the simulation output waveform samples (1 to 128) were compared to the input. The detailed DFB simulation also produced a simulated set of CAL2 output waveform samples.

The detailed DFB simulation could only do CAL2 at fixed values of the fine-height word, but the on-board TOPEX altimeter hardware performs CAL2 using a continuous sweep of the height. The detailed DFB simulation produced different CAL2 waveforms for fine-height values of 0 and ± three samples (*i.e.*, 0 ± 9.375 ns). There did not appear to be significant (simulated) CAL2 changes with fine-height value, so the average of the three simulated CAL2 waveforms was used.

Figure 4 summarizes the waveforms in and out of the detailed DFB simulation for the Topex Ku-band altimeter at 0.0 degrees attitude angle. The "+" symbols show the model waveform used as input to the detailed DFB simulation, and the diamond symbols show the DFB simulation output. The simulation CAL2 result was converted into a set of gains used to "correct" the DFB simulation output, with the result shown by the solid line in Figure 4. The Figure 4 results were scaled so that the sums of telemetry samples 9 to 40 (waveform samples 17 to 48) are the same for the three curves presented. Notice that the figure shows the 64 telemetry sample results, but plotted on the equivalent waveform sample range of 1 to 128.

Comparing input ("+" symbols) to CAL2-corrected output (solid lines) in Figure 4, there are two different effects: i) extra signal in the waveform plateau, and ii) non-zero baseline in the noise region of the waveform. Both of these effects seem to be present in the on-orbit TOPEX altimeter data. In these comparisons, one should ignore the first and last four telemetry samples (waveform samples 1 to 8, and 113 to 128) since they may be affected by the bandpass filter and its wraparound (discussed later).

In the WALTOPEX simulations producing the correction coefficients for the current ground processing, the plateau excess is compensated by multiplicative corrections derived from the detailed DFB simulations. Fine-height dependence has been ignored to date in these corrections, but further simulation study is needed. The plateau excess is a troublesome effect because its waveform effects, if not corrected, can be interpreted as an off-nadir pointing angle or as an increased effective antenna beamwidth.

DFB Effects Which Depend Upon The Fine-Height Word

The altimeter's range is the sum of the coarse-height word (s) and fine-height word. The least significant bit of the coarse-height word is 12.5 ns in ranging time units, while the fine-height word range is 0-25 ns. When the range rate is negative (the height is decreasing), the height is kept in the upper half of the fine-height word. If the tracked range moves to the lower part of the fine-height word, the coarse-height is reduced by 12.5 ns and the fine-height is increased by 12.5 ns; the sum of the coarse-height and fine-height is the same but the tracked range will have been moved back to the upper half of the fine-height word. Similarly for increasing range the tracked range is kept in the lower half of the fine-height word.

As the TOPEX altimeter moves from a latitude extreme (either plus or minus 66 degrees) toward the equator, the height rate is negative. After the equator, the height rate is positive. Consequently the fine-height word will be in its upper half for Northern hemisphere North-to-South passes and Southern hemisphere South-to-North passes. The fine-height will be in its lower half for Northern hemisphere South-to-North passes and Southern hemisphere North-to-South passes.

Filter bank end fall-off: The shape of altimeter's receiver video bandwidth is dominated primarily by the anti-aliasing filter. (*Chelton et al.* [1989] describe the need for the anti-aliasing filter.) For different fine-height values, the receiver's video bandwidth shape is moved horizontally relative to the individual waveform samples. Figure 5 sketches the effect for three different fine-height values, and the effect can also be seen in the CAL2 data plotted in Figure 3. In this mode, the altimeter looks at noise only, and the AGC adjusts the receiver gain to attain a preset level. If the DFB created a replica of receiver input noise, there should be a fixed level seen across the entire band. The anti-aliasing filter modifies this, and the effects are seen at the low and high ends of the bandwidth. In CAL2 the fine-height word's least significant bit (approximately 0.05 ns) is incremented constantly. The fine-height word will increase to its maximum of 25 ns, then start increasing again from zero. Consequently successive averages will show the anti-aliasing filter shape moving relative to the waveform samples.

Wraparound effect: At small values of fine height the filter bandpass is shifted upward and some of the energy coming through the filter bandpass will fall past the extent of the filter bank. This extra energy which should be at the end of the pulseshape will be wrapped around to the early waveform samples.

Leakage effects: In the investigations of other anomalies in TOPEX altimeter waveforms, various low level "spikes" were found in some waveform samples. These were often referred to as leakage. The power of the leakage spikes is independent of receiver gain (AGC), and the location of these spikes in the waveform sample set moves with fine height value. These leakage spikes probably enter the altimeter just at or just after the A/D conversion of the I and Q video output of the receiver, and Table 2 lists these features by designation, amplitude, and sample number location. Figure 6 sketches the location of these spikes and their relative magnitudes for the fine-height word at the middle of its range (i.e., at the highest height word value for positive height rate, or the lowest height word value for negative height rate). All these leakage effects are small, about 200 counts or less, compared to the AGC value of 4096 counts and the waveform peak of the order of 8000 counts. Figure 6 also indicates the locations of various gates including the early (E), middle (M), and late (L) gates used in tracking. E5, M5, L5 and E4, M4, L4 are the track gates for gate index values 5 and 4, and are indicated by labelled horizontal lines in the figure. The E, M, L gates for gate index values 3, 2, and 1 are shown but labels are omitted to avoid an excessively cluttered figure. (See *Zieger et al.* [1991] for a description of how the E, M, and L gates are used in the on-board range and SWH estimation). Figure 6 also sketches the locations of the G_{egt}, G_{agc}, and G_{att} used in producing V_{ATT} in the ground processing.

One way to see the leakages more clearly in the altimeter was to examine Standby Mode waveforms in a transmitter test mode. In Standby Mode, the 64 telemetry samples contain the center 64 waveform samples. In the transmitter test mode the height is continuously incremented, either up or down, so the fine height word will sweep over either the upper or the lower half of its range depending on the sign of the height rate. Only the leakages affecting track-mode telemetry samples 25 to 56 can be seen in this test mode, and the test must be run in two halves, each with a different sign of height rate, to see the full range over which a leakage spike will move.

Another way to see the leakage spikes has been to run a special CAL2 test with the AGC attenuator set at a high level (approximately 25 dB) to attenuate the normal noise signal far enough that the small leakage spikes can be seen more clearly. The difficulty with this test mode is that some of the non-central leakages are made more difficult to see by the factor-of-2 or factor-of-4 averaging in the telemetry samples.

Because the leakage spikes are so small and these test modes so relatively noisy, the interpretation of the test data is highly subjective. The Table 2 characterizations of leakage spike amplitude could be in error by as much as 50%, and the waveform sample locations could be incorrect by perhaps one sample.

Offset leakage spike: There is leakage in the center of the waveform sample set, at sample 65 ± 4 depending on fine height word, which is designated as offset leakage in Table 2. This offset leakage, is difficult to separate from the zero-frequency leakage (from truncation in digital FFT), but the offset leakage does move with fine-height word (unlike the zero-frequency leakage which does not). This offset leakage is believed to result form a slight offset in biasing of the A/D convertor, based on some tests with existing engineering model and breadboard hardware. The engineering model DFB had an offset leakage whose behavior was approximately the same as the flight unit. The breadboard DFB did not originally exhibit the offset leakage but the offset leakage could be made to appear by changing the value of the biasing resistor on the A/D convertor in the I channel. The resistor was adjusted until the breadboard DFB offset leakage matched that of the engineering model; this work indicates that the flight unit offset leakage is about 3/8 of the least significant bit in the I-channel A/D.

Other (numbered) leakage spikes: In the flight unit Side A there are several other spikes which are of the order of 100 counts or less, and these are designated by numbers 1 to 8 in Table 2. These spikes are probably caused by low level signal leakage into the receiver chain after the AGC adjustments but before the actual FFT process. There is no AGC effect on their amplitude, but there does seem to be some temperature variation of their amplitudes. This temperature variation was found by reexamining some of the test data. The positions of most of these leakage spikes can be correlated with harmonics of the low voltage power supply switching frequencies, specifically 300, 400, 450, and 500 kHz; the power supply is known to generate these frequencies, based on unit EMF test. Notice that spikes #4 and #5 are approximately equidistant from the zero-frequency sample at the center of the waveform sample set. Similarly spikes #3 and #6, #2 and #7, and #1 and #8 are also pairwise equidistant about the center. These particular (numbered) leakage spikes are present only in the flight unit Side A, but were only discovered and investigated after the TOPEX/POSEIDON launch. Before launch, Side A had been chosen as the prime altimeter because of minor concerns on reliability of some components (*i.e.*, switches and UCFM) in Side B. All the on-orbit data have come from Side A, and Side B will never be operated except in the event of a failure of Side A.

Of the numbered leakage spikes in Table 2, the most worrisome is #4 because of its position relative to the TOPEX altimeter tracking gates; this can been seen in Figure 6. All the spikes in Figure 6 will move by ±4 samples relative to their plotted center positions, depending on the value of the fine height word, and this moves spike # 4 in and out of the track gates. Simulation studies both at the Johns Hopkins University Applied Physics Laboratory and at the Goddard Space Flight Center's Wallops Flight Facility indicate that the tracking errors arising from leakage spike #4 should generally be 1 centimeter or less for most operating conditions of general interest, but further study is needed.

Correction/Compensation for Waveform Effects

Waveform samples to avoid: Because of the zero-leakage and the offset leakage effects, any ground-based waveform processing should avoid using waveform sample 65 and at least 4 samples to either side of 65. Waveform fitting at WFF has skipped (by assigning zero weights to) telemetry samples 45 to 50, corresponding to waveform samples 57 to 72. Likewise, to avoid effects of fall-off and wraparound, telemetry samples 1 to 4 and 61 to 64 (waveform samples 1 to 8 and 113 to 128) have been avoided in all WFF waveform fitting work.

Multiplicative and additive factors: The several waveform effects can be partially compensated or corrected by sets of multiplicative and additive waveform factors. For each telemetry sample $T_{s,i}$ there is an additive adjustment A_i and a multiplicative adjustment G_i to produce a corrected waveform $W_{c,i}$,

$$W_{c,i} = G_i \times (T_{s,i} + A_i) ,$$

for i from 1 to 64. The multiplicative adjustments, which are obtained from a combination of the CAL2 data and modeling, compensate for the sawteeth, zero-frequency leakage, plateau excess, and end fall-off.

The additive adjustments A_i compensate for the leakage effects but only in a way that averages over all possible fine height values. The spikes in Figure 6 are for the fine height at the middle of its entire range (i.e., at the highest value in the lower half or the lowest value of the upper half). The fine height value is not available in the current implementation of the

TOPEX altimeter ground data processing; the fine height is added to the coarse height early in the ground processing flow (within the Engineering Units Conversion module), and is not separately available thereafter. Since the fine height value is not available for ground post-processing we have treated the spikes as a probabilistic smear over all their possible positions. Figure 7 shows the spikes of Figure 6 as smeared over ± 4 waveform sample positions. It would be possible to halve the width of the smear by treating data differently for increasing than for decreasing height rate, but that has not been done to date.

Table 3 gives the Ku-band and C-band multiplicative and additive correction factors which are currently in the routine TOPEX altimeter ground processing at JPL. The additive factors are based on somewhat earlier leakage analyses than Figure 6 and 7 and Table 2. Specifically, spikes #7 and #8 were not used, and the two offset leakage spikes were used. These differences should be unimportant, because the offset leakage is not in any of the gates, and spike #7 contributes only a very small amount to the V_{ATT} attitude gate used in attitude corrections in the ground-based processing. The Table 3 factors are currently used in various waveform fitting analyses at WFF.

Example: Figure 8 shows a typical input waveform (from scaled telemetry samples), the corrected waveform after application of the additive and multiplicative factors, and the waveform which is least-squares fitted to the corrected waveform. In this figure there is some fall-off and wraparound still visible, and there is still some extra energy in the vicinity of equivalent waveform sample 64. The waveform in this figure is the same 5-second average already shown earlier in Figure 2.

TYPICAL RESULTS

The examples in this section are from waveform fits to 10-second waveform averages. The skewness has been set to 0.1 and the remaining five model waveform parameters have been varied in these fits. We will first show examples from regions of relatively high SWH but low attitude values, and then will show an example from a larger attitude excursion.

High SWH Example

We selected a high SWH segment from each of seven passes from Cycle 009, for total of 312 10-second waveform averages. Figure 9a shows waveform fit SWH vs. time for these seven segments of data, and each segment has had a different time subtracted so that the data could be displayed on a common time scale. The seven distinct segments are easily seen, and the data have been given different plot symbols for the different gate selection index (igt) values. The waveform fit attitude estimates for these data are shown in Figure 9b.

Figure 10a shows the waveform fit estimate of range correction, again identified by igt value. Figure 10b shows the difference in range correction, to assess how well the coefficient-based range corrections reproduce the results from waveform fitting; the difference plotted is the waveform fit range correction minus the coefficient-based correction (*i.e.*, the correction estimated from the V_{SWH}, V_{ATT}, and the correction coefficients in the current TOPEX altimeter ground processing). From the data of Figure 10b , we find the following values for the range correction difference (waveform fit minus coefficient-based): -2±5 mm for gate index 2; -11±11 mm for gate index 3; and +5±14 mm for gate index 4. A larger set of data should be examined and results should be separated into two classes, depending on which half of the fine height word was used, but the small values of these range correction differences do confirm that the coefficient-based range correction does match the waveform fit results at the centimeter level.

For this Cycle 009 data set, we also compared the final coefficient-corrected SWH to that derived from the waveform fitting, and found these following values for the waveform fit SWH minus the coefficient-based SWH: 0.0±0.2 meters for gate index 2; 0.0±0.4 m for gate index 3; and -0.2±0.6 m for gate index 4. These values are contaminated by several relatively large outliers. With tighter editing criteria the rms value for gate index 4 would be only about 0.1 meters. Again, further work with a larger data set would be useful, but the current coefficient-based SWH is already in very good agreement with the waveform fit SWH.

Typical ABCAL Sequence

As part of the process of improving performance of the spacecraft's attitude control system, the TOPEX Project has carried out a series of over-ocean attitude bias calibration maneuvers (ABCALs). From October 1992 through September 1993 there were sixteen ABCALs with the NASA altimeter operating, and five with the CNES altimeter operating. In the current form of an ABCAL, the spacecraft control system drives the attitude angle off-nadir in a cross-shaped maneuver with a maximum off-nadir angle of about 0.45 degrees in each of four directions (±x and ±y, where x is along the spacecraft ground track). The total maneuver takes about 14 minutes.

Figure 11a shows the waveform fit SWH estimates for ABCALs #20 and #21; ABCAL #20 was in Pass 176, Cycle 26, 04 June 1993, and ABCAL #21 was in Pass 247, Cycle 36, 14 September 1993. The time axis of Figure 11a is the time relative to the ABCAL start, and ABCAL #21 has been displaced by 1200 seconds to avoid overplotting. Figure 11b shows the attitude estimates, with the eight (four per ABCAL) excursions out to about 0.45 degrees. Figure 12a shows the waveform fit range corrections, and Figure 12b shows the range correction differences (fit minus coefficient-based). There is perhaps a small bias between the gate index 2 and index 3 data on Figure 12b but, as in the high-SWH examples, the range correction agreement is within a centimeter.

STATUS

Almost immediately upon receiving the first on-orbit TOPEX altimeter data, we found that the V_{ATT} term in the C-band altimeter corrections was introducing too much noise into the results. The C-band corrections are a much less strong function of attitude angle than are the Ku-band corrections, and we found it adequate to make the C-band corrections solely as a function of the C-band V_{SWH}. During the first half year of TOPEX altimeter on-orbit operation (the evaluation period) approximately a half dozen new sets of range (and AGC and SWH) correction constants were generated by our simulation procedure, each simulation incorporating then-current knowledge of the various waveform features. Our last version of waveform effects modeling was used in an interim set of constants produced in April 1993; then one final adjustment was made in May 1993, when the Ku-band range correction for gate index 3 was increased by 1.0 cm. The 1 cm change was made for better agreement of the range corrections with preliminary results from waveform fitting research being done at JPL [E. Rodriguez, personal communication] and represents the only occasion that simulation-based constants were adjusted based on waveform fitting results. This May 1993 set of constants is the set used in the current TOPEX altimeter ground data processing system, and used in the data comparisons of Figures 13 and 17.

From launch until Pass 189, Cycle 008, in early December 1992, the attitude varied over each pass by as much as 0.4 degrees. During Pass 189/008 the TOPEX Project uploaded important improvements to the spacecraft attitude control system, and attitude control since then has been superb with attitude values consistently less than 0.10 degrees.

CONCLUSION

Range corrections for SWH and attitude do appear adequate at about the centimeter level. Below this level, it would be necessary to consider detailed fine height effects, and this is not possible to do in the production TOPEX altimeter data processing; the fine height and coarse height values are separately telemetered, but are merged in one of the early steps in the current ground processing.

Our waveform fitting results do seem to confirm the choice of the current set of processing constants for the range corrections for effects of significant waveheight and attitude. Some small improvements could conceivably be made, based on more extensive analyses, but we see no compelling argument for changes in the ground processing constants.

We have described our current understanding of the TOPEX altimeter waveform features which arise from the DFB, hoping that this information will be useful to others investigating waveform processing. Although we wish the waveform features had been smaller, we found by comparing CAL2 telemetry sample data for more than a year of TOPEX altimeter operation that the individual samples were stable to better than 1% of their maximum magnitude and therefore met the original hardware specification for waveform sampling.

Considerable clarification has been gained from recent laboratory testing of engineering model components, but we stress the importance of further testing and understanding of waveform features for any future radar altimeters.

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from the digital filter bank. J. R. Jensen of JHU/APL contributed important DFB detailed simulations clarifying the relationship of FFT hardware details to observed waveform features.

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FIGURE CAPTIONS

Fig. 1. TOPEX Ku altimeter range corrections as a function of significant waveheight, for different attitude angles.

Fig. 2. Typical TOPEX Ku altimeter telemetry sample five-second average waveform.

Fig. 3. TOPEX Ku altimeter telemetry sample ten-second averages from two different day's CAL2 modes.

Fig. 4. TOPEX Ku altimeter model waveform and detailed DFB simulation results.

Fig. 5. TOPEX altimeter video filter shape for different values of the fine height word.

Fig. 6. TOPEX Ku altimeter gates, mean return, and center locations of waveform leakage spikes.

Fig. 7. TOPEX Ku altimeter gates, mean return, and smeared locations of waveform leakage spikes.

Fig. 8. Comparison of input and corrected telemetry samples to a fitted waveform for typical TOPEX Ku altimeter five-second data averages.

Fig. 9. TOPEX Ku altimeter waveform fit results for selected high-SWH Ku altimeter data regions in TOPEX cycle 009. (a) Significant waveheight estimates. (b) Attitude angle estimates.

Fig. 10. TOPEX Ku altimeter waveform fit results for selected high-SWH Ku altimeter data regions in cycle 009. (a) Range correction estimates from waveform fitting. (b) difference between waveform-fit-estimated and correction-coefficient-estimated range corrections.

Fig. 11. TOPEX Ku waveform fit results for data from ABCALs 20 and 21 (ABCAL 21 displaced by 1200 seconds). (a) Significant waveheight estimates. (b) Attitude angle estimates.

Fig. 12. TOPEX Ku altimeter waveform fit results for data from ABCALs 20 and 21 (ABCAL 21 displaced by 1200 seconds). (a) Range correction estimates from waveform fitting. (b) difference between waveform-fit-estimated and correction-coefficient-estimated range corrections.

Table 1. TOPEX Telemetry Sample to Waveform Sample Relationship for Different Altimeter Modes

Telemetry Sample #	Waveform Sample # for TRACK or CAL MODE 2	Waveform Sample # for CAL MODE 1, STANDBY, or TRANSMITTER TEST
1 ... 8	1 - 2 ... 15 - 16	33 ... 40
9 ... 40	17 ... 48	41 ... 72
41 ... 48	49 - 50 ... 63 - 64	73 ... 80
49 ... 64	65 - 69 ... 125 - 128	81 ... 96

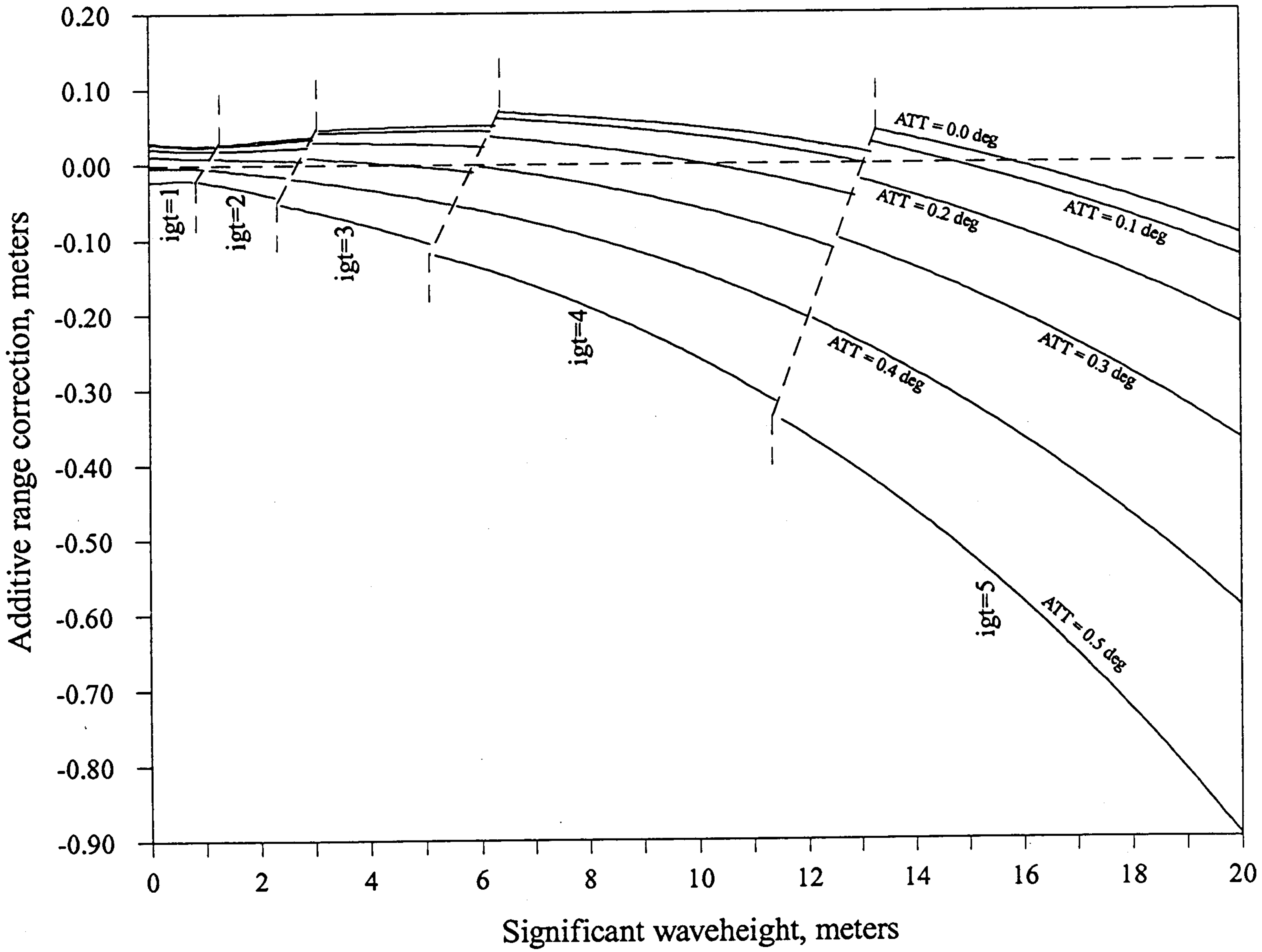
Table 2. Characterization of TOPEX Ku Waveform Leakage Spikes

Spike designation	Amplitude, counts	Waveform sample # range	TLM sample # range (track mode)
offset leakage	300	61 - 69	47 - 49
1	50	10 - 18	6 - 10
2	50	15 - 23	8 - 15
3	100	20 - 28	12 - 20
4	110	30 - 38	22 - 30
5	120	92 - 100	55 - 57
6	100	102 - 109	58 - 60
7	60	106 - 114	59 - 61
8	30	111 - 119	60 - 62

Table 3. TOPEX Waveform Correction Factors

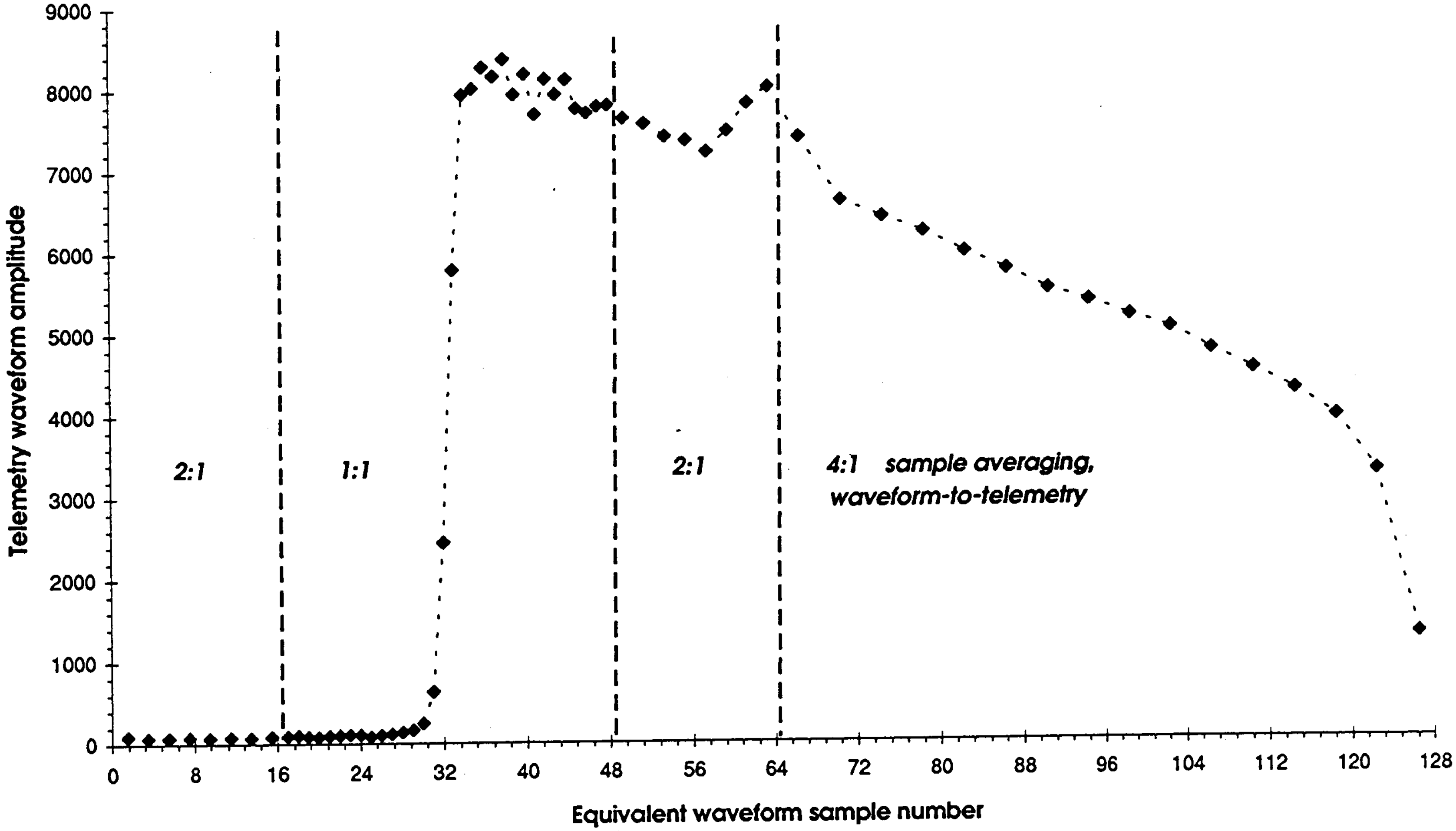
Telemetry sample #	Multiplicative factors	Ku additive factors	C additive factors	Telemetry sample #	Multiplicative factors	Ku additive factors	C additive factors
1	3.355	0	0	33	1.007	0	0
2	2.327	0	0	34	0.958	0	0
3	1.638	0	0	35	0.981	0	0
4	1.178	0	0	36	0.956	0	0
5	1.120	-1.39	-0.35	37	0.976	0	0
6	1.083	-2.78	-0.69	38	0.960	0	0
7	1.065	-2.78	-0.69	39	0.986	0	0
8	1.047	-9.44	-2.36	40	0.953	0	0
9	1.070	-9.44	-2.36	41	0.966	0	0
10	1.025	-9.44	-2.36	42	0.955	0	0
11	1.041	-6.67	-1.67	43	0.955	0	0
12	1.025	-17.78	-4.44	44	0.947	0	0
13	1.036	-17.78	-4.44	45	0.945	0	0
14	1.012	-17.78	-4.44	46	0.941	-15.56	-3.89
15	1.029	-17.78	-4.44	47	0.913	-57.78	-14.44
16	1.009	-11.11	-2.78	48	0.882	-57.78	-14.44
17	1.037	-11.11	-2.78	49	0.868	-57.78	-14.44
18	0.999	-11.11	-2.78	50	0.909	-6.67	-1.67
19	1.023	-11.11	-2.78	51	0.934	0	0
20	1.002	-11.11	-2.78	52	0.932	0	0
21	1.006	0	0	53	0.937	0	0
22	0.992	-11.11	-2.78	54	0.932	0	0
23	1.005	-11.11	-2.78	55	0.945	-2.78	-0.69
24	0.987	-11.11	-2.78	56	0.948	-11.11	-2.78
25	1.027	-11.11	-2.78	57	0.954	-11.11	-2.78
26	0.987	-11.11	-2.78	58	0.936	-11.11	-2.78
27	0.997	-11.11	-2.78	59	0.949	-11.11	-2.78
28	0.981	-11.11	-2.78	60	0.957	-2.78	-0.69
29	0.990	-11.11	-2.78	61	0.983	0	0
30	0.979	-11.11	-2.78	62	1.013	0	0
31	0.997	0	0	63	1.158	0	0
32	0.969	0	0	64	2.273	0	0

Fig. 1



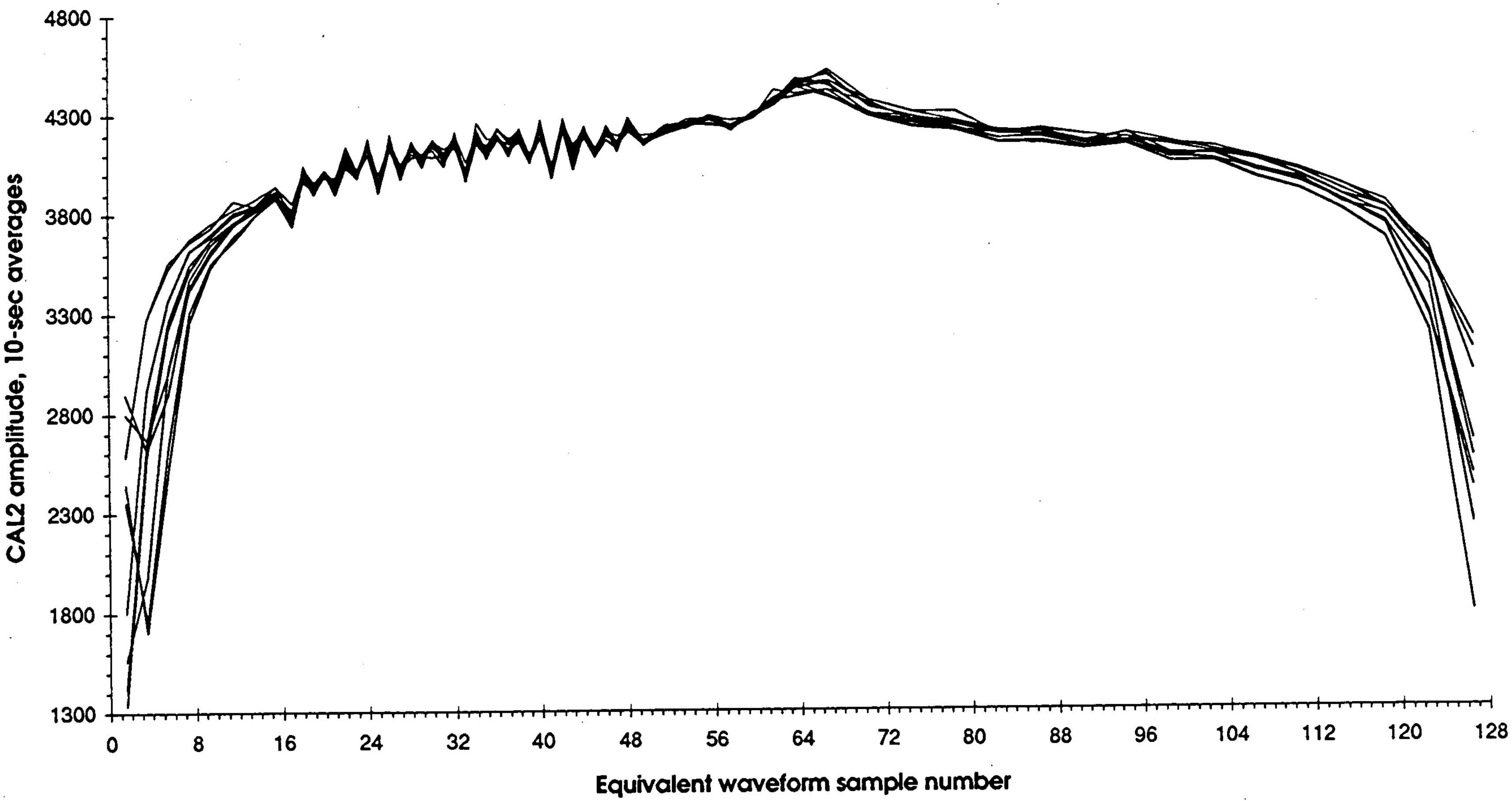
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
-0.80
-0.90
Additive range correction, meters
0
2
4
6
8
10
12
14
16
18
20
Significant waveheight, meters
igt=1
igt=2
igt=3
igt=4
igt=5
ATT = 0.0 deg
ATT = 0.1 deg
ATT = 0.2 deg
ATT = 0.3 deg
ATT = 0.4 deg
ATT = 0.5 deg

Fig. 2



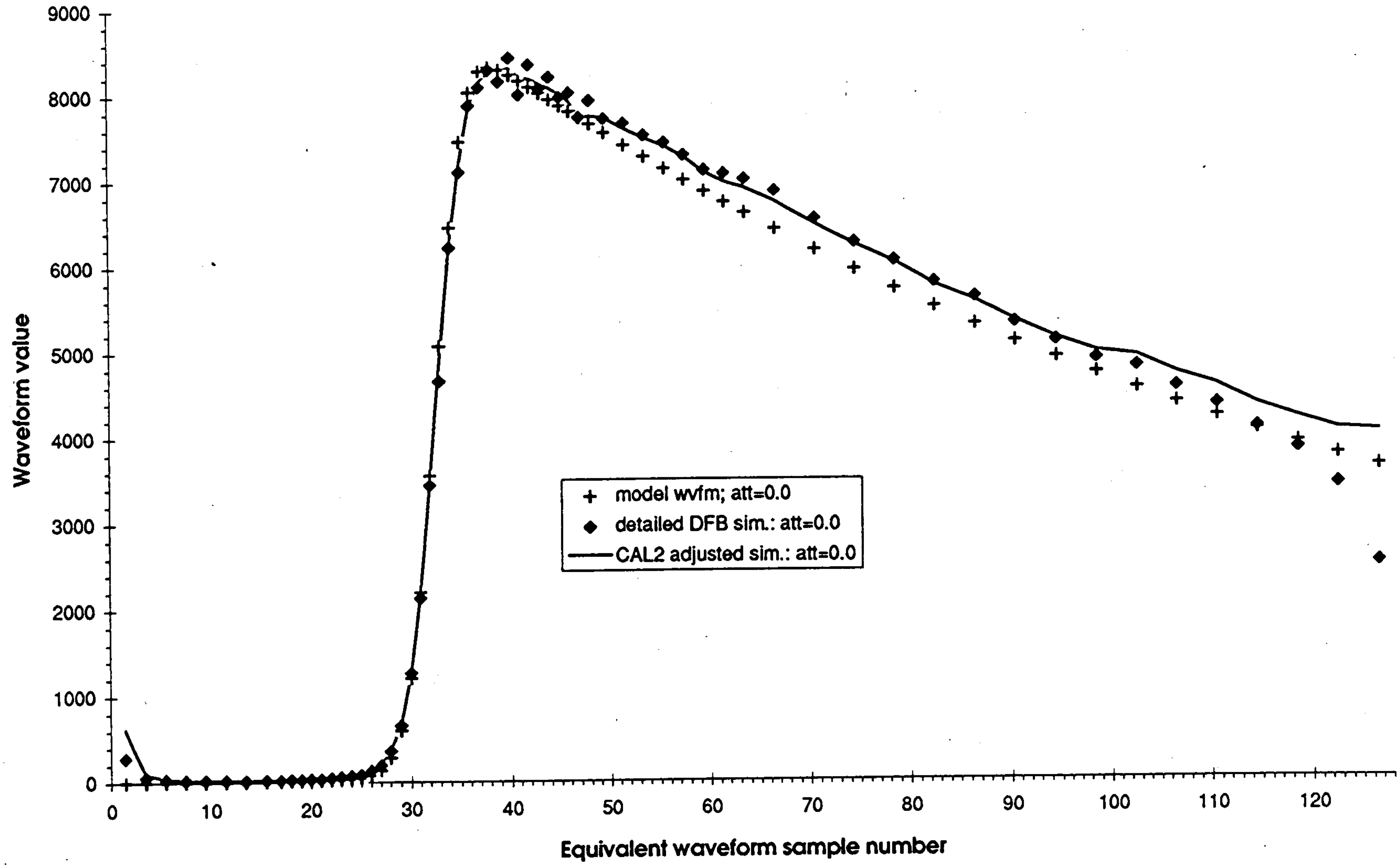
Telemetry waveform amplitude
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2:1
1:1
2:1
4:1 sample averaging,
waveform-to-telemetry
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
Equivalent waveform sample number

Fig. 3



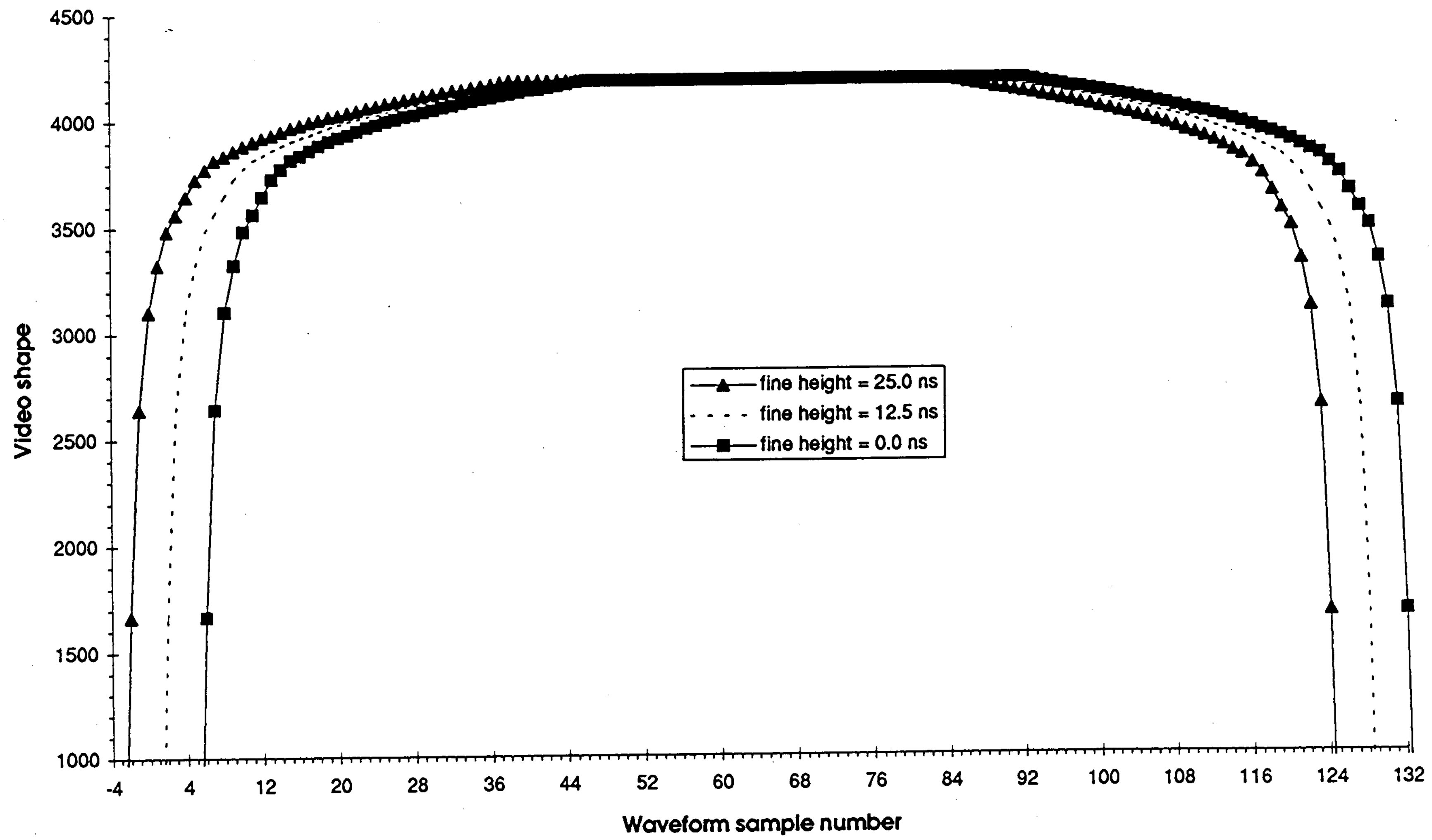
CAL2 amplitude, 10-sec averages
4800
4300
3800
3300
2800
2300
1800
1300
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
Equivalent waveform sample number

Fig. 4



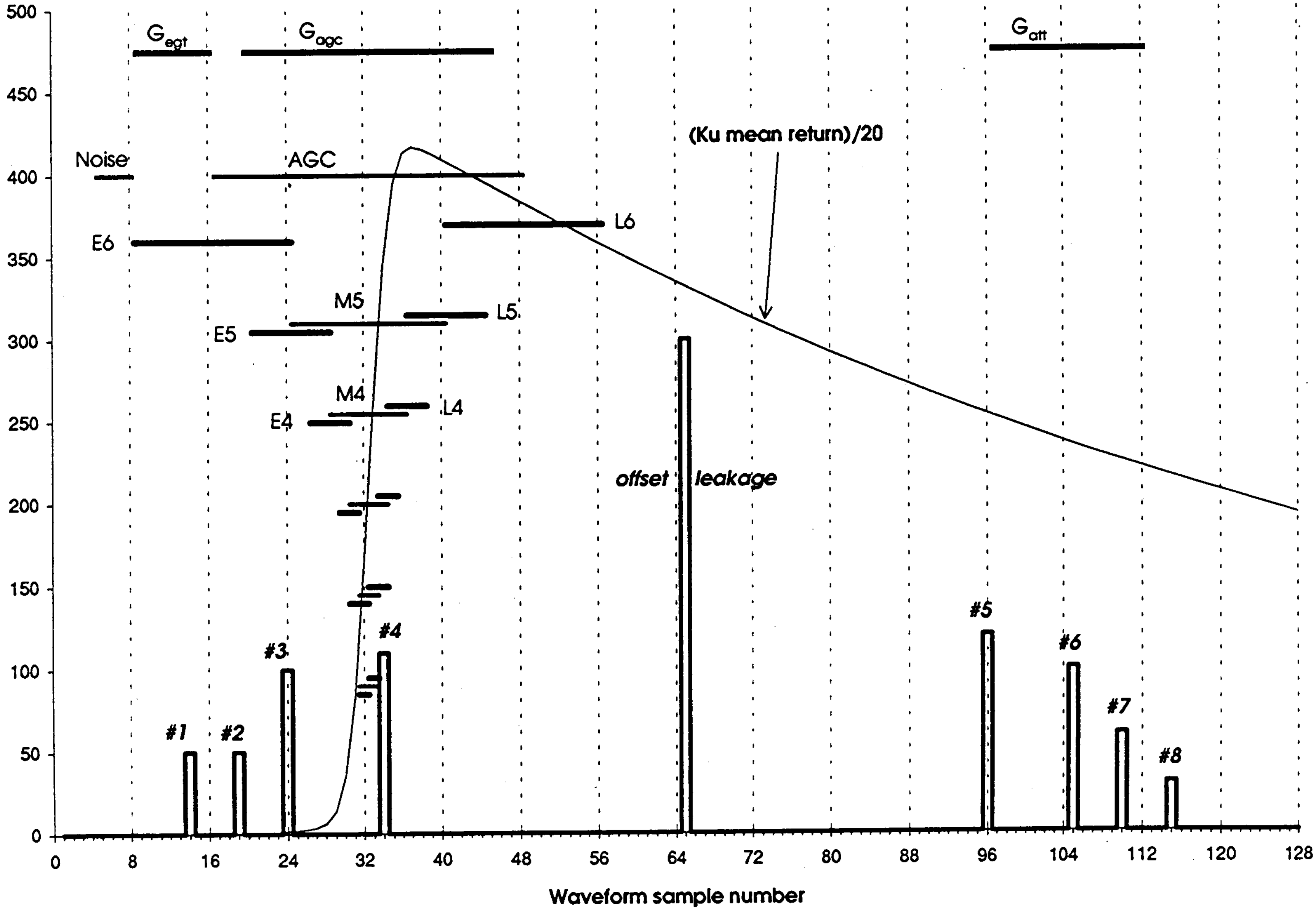
Waveform value
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Equivalent waveform sample number
model wvfm; att=0.0
detailed DFB sim.: att=0.0
CAL2 adjusted sim.: att=0.0

Fig. 5



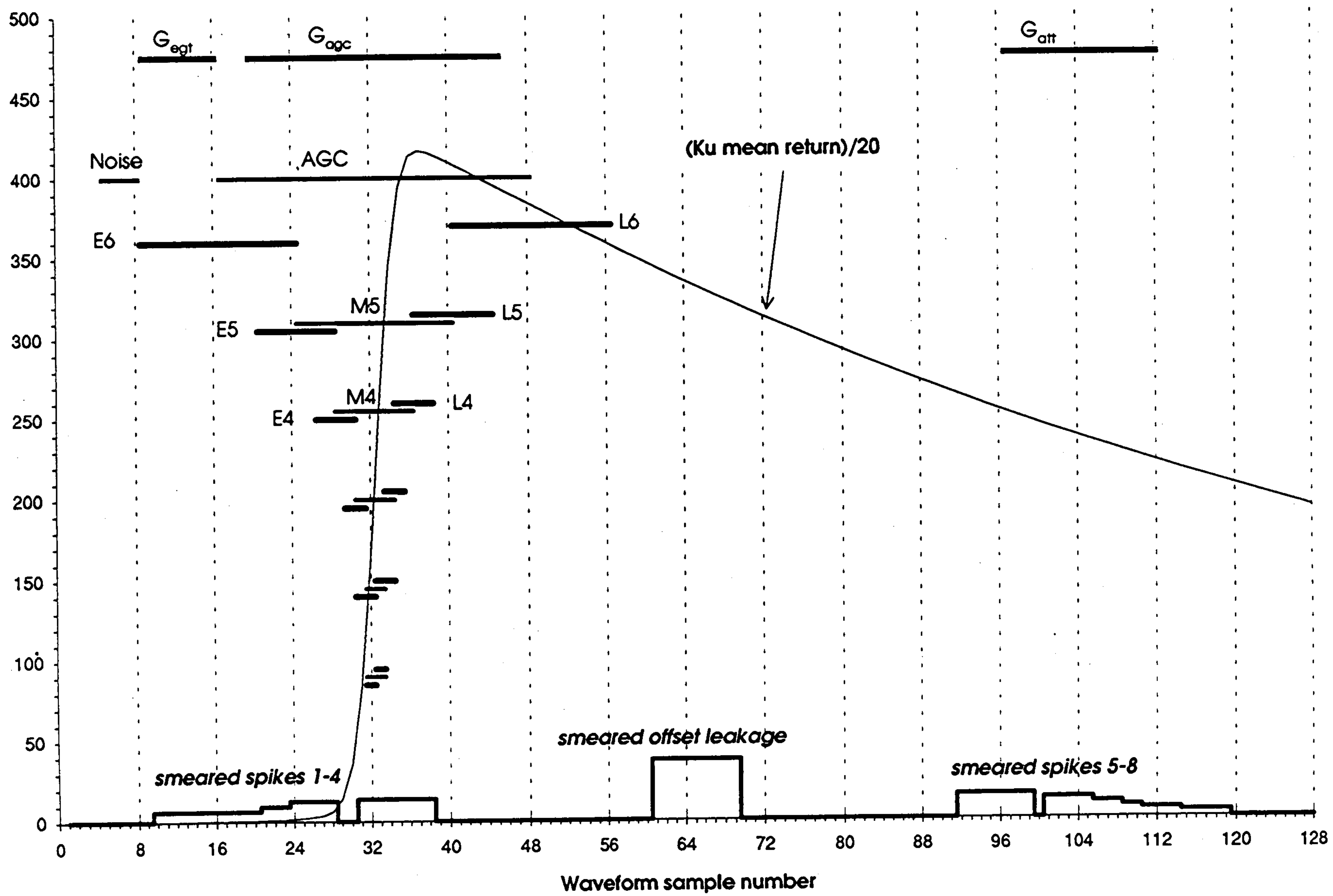
Video shape
4500
4000
3500
3000
2500
2000
1500
1000
-4
4
12
20
28
36
44
52
60
68
76
84
92
100
108
116
124
132
Waveform sample number
fine height = 25.0 ns
fine height = 12.5 ns
fine height = 0.0 ns

Fig. 6



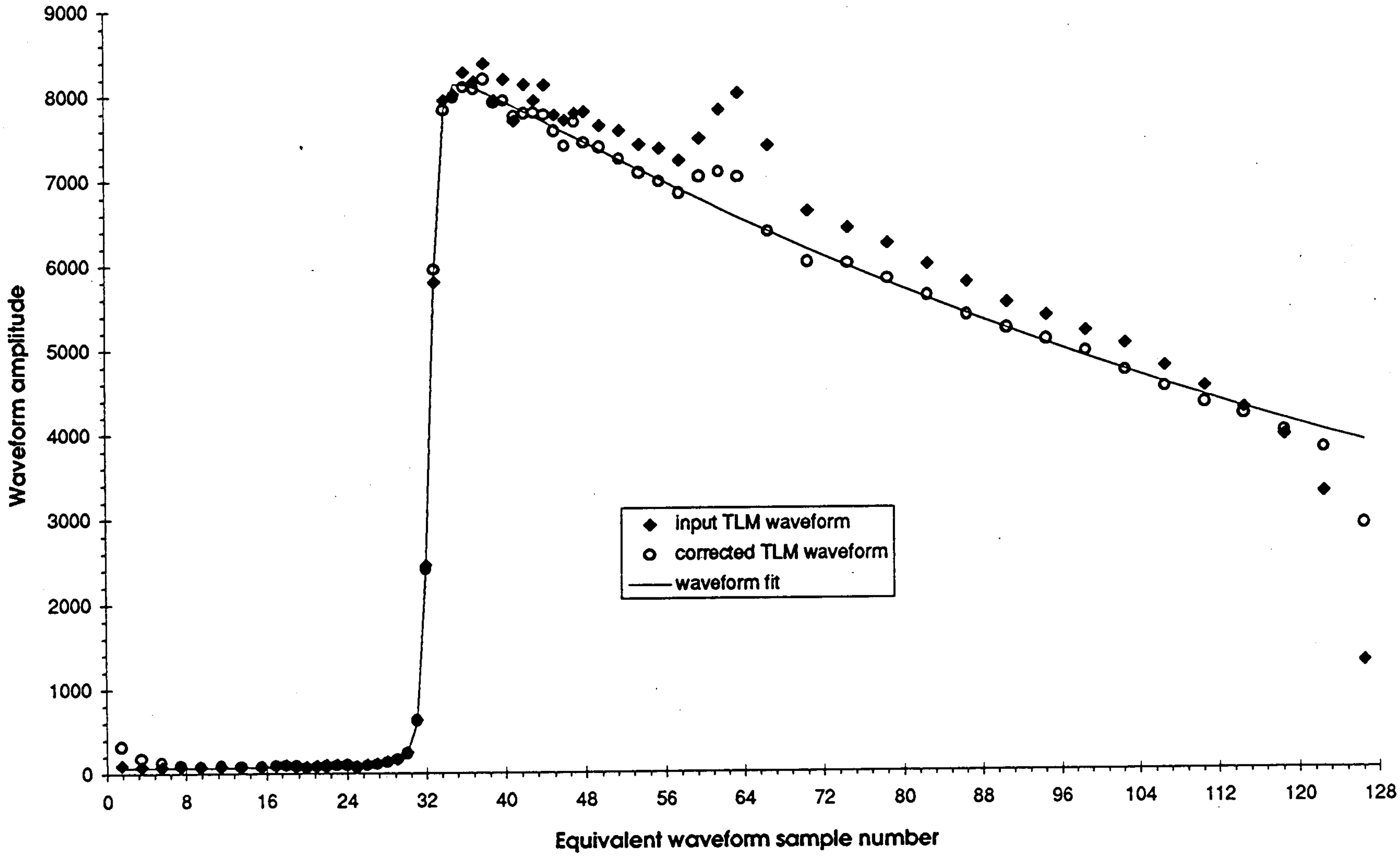
500
450
400
350
300
250
200
150
100
50
0
G_{egt}
G_{agc}
G_{att}
Noise
AGC
E6
L6
M5
L5
E5
M4
L4
E4
(Ku mean return)/20
offset leakage
#1
#2
#3
#4
#5
#6
#7
#8
0 8 16 24 32 40 48 56 64 72 80 88 96 104 112 120 128
Waveform sample number

Fig. 7



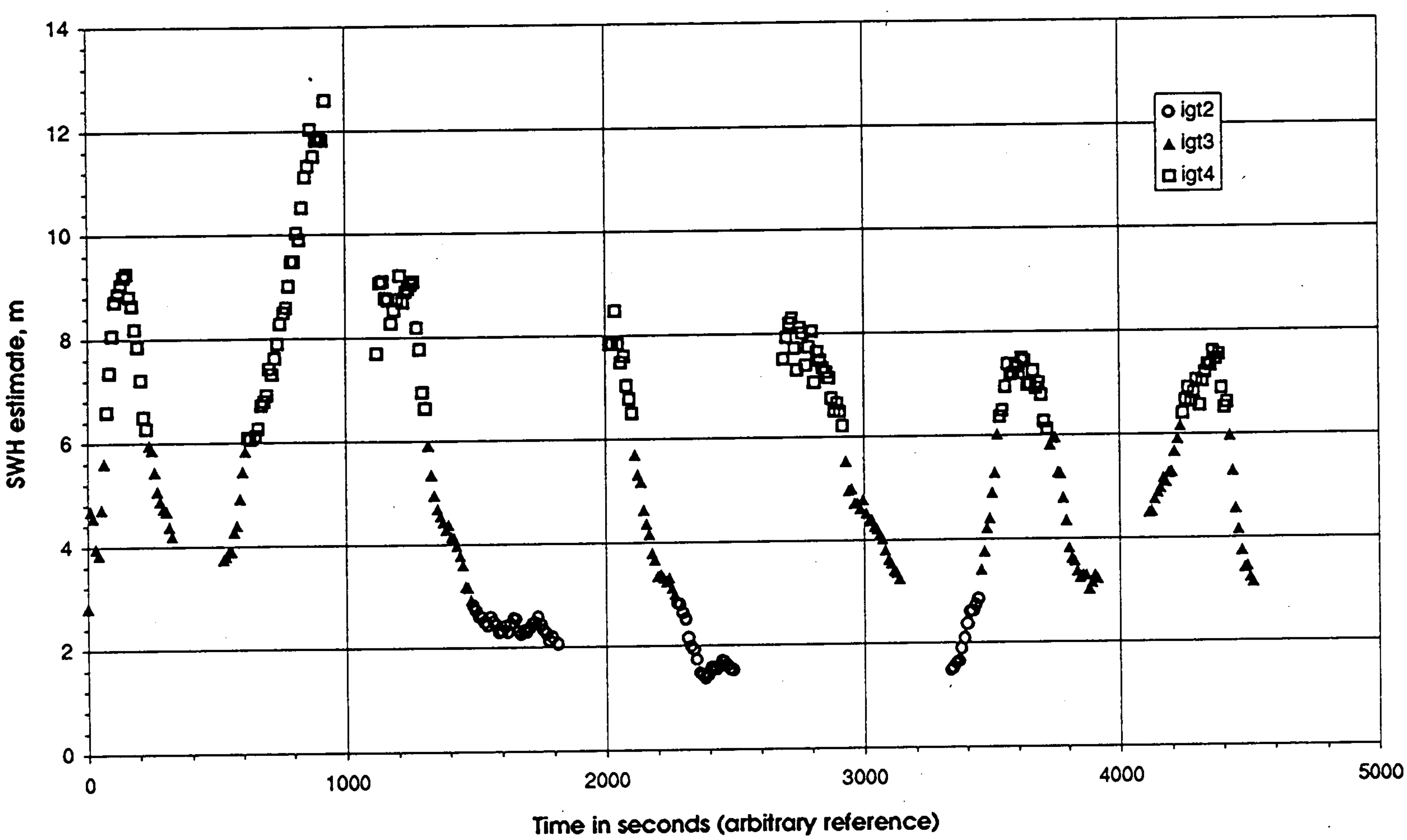
500
450
400
350
300
250
200
150
100
50
0
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
Waveform sample number
G_{egt}
G_{agc}
G_{att}
Noise
AGC
E6
L6
(Ku mean return)/20
M5
L5
E5
M4
L4
E4
smeared spikes 1-4
smeared offset leakage
smeared spikes 5-8

Fig. 8



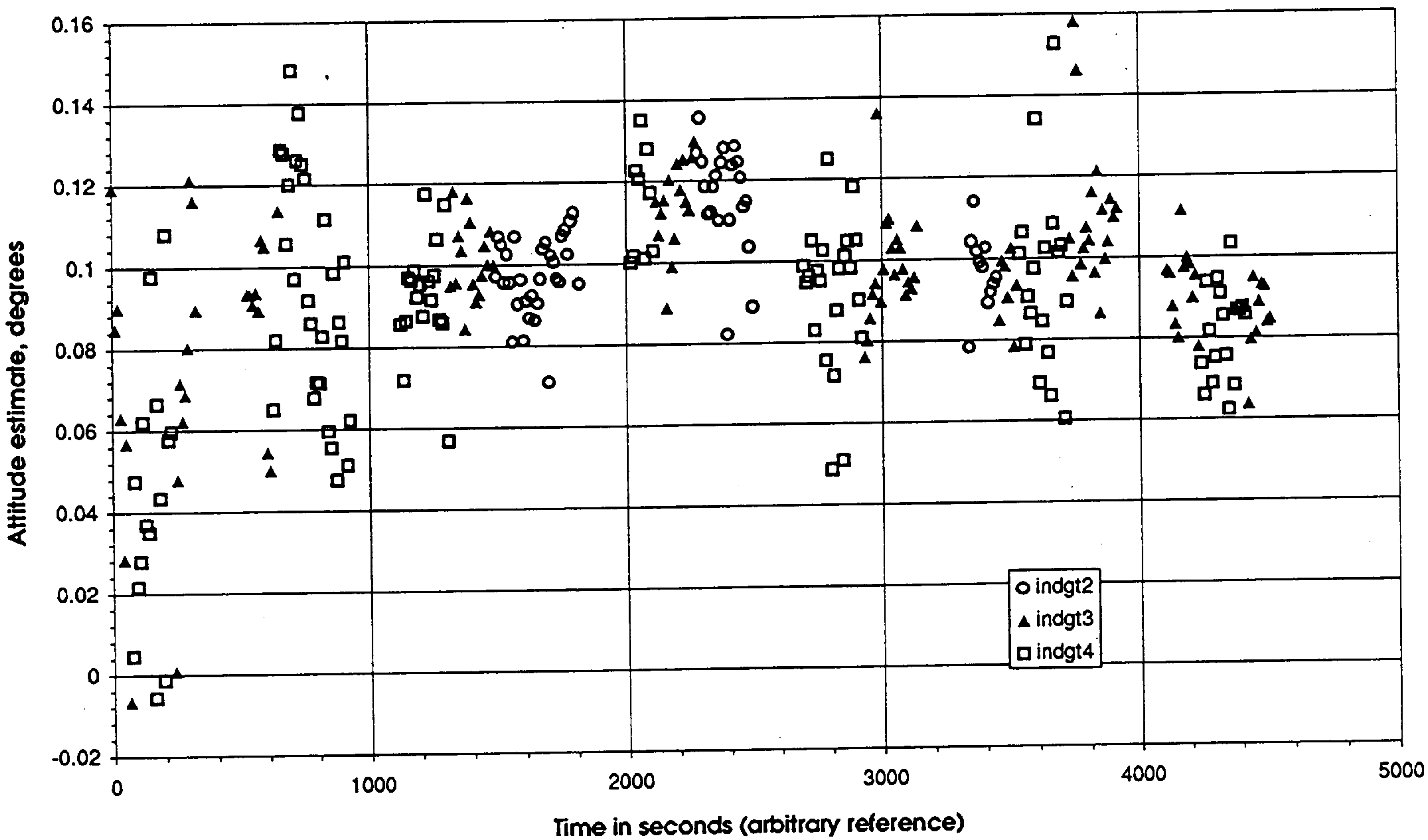
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Waveform amplitude
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
Equivalent waveform sample number
input TLM waveform
corrected TLM waveform
waveform fit

Fig. 9a



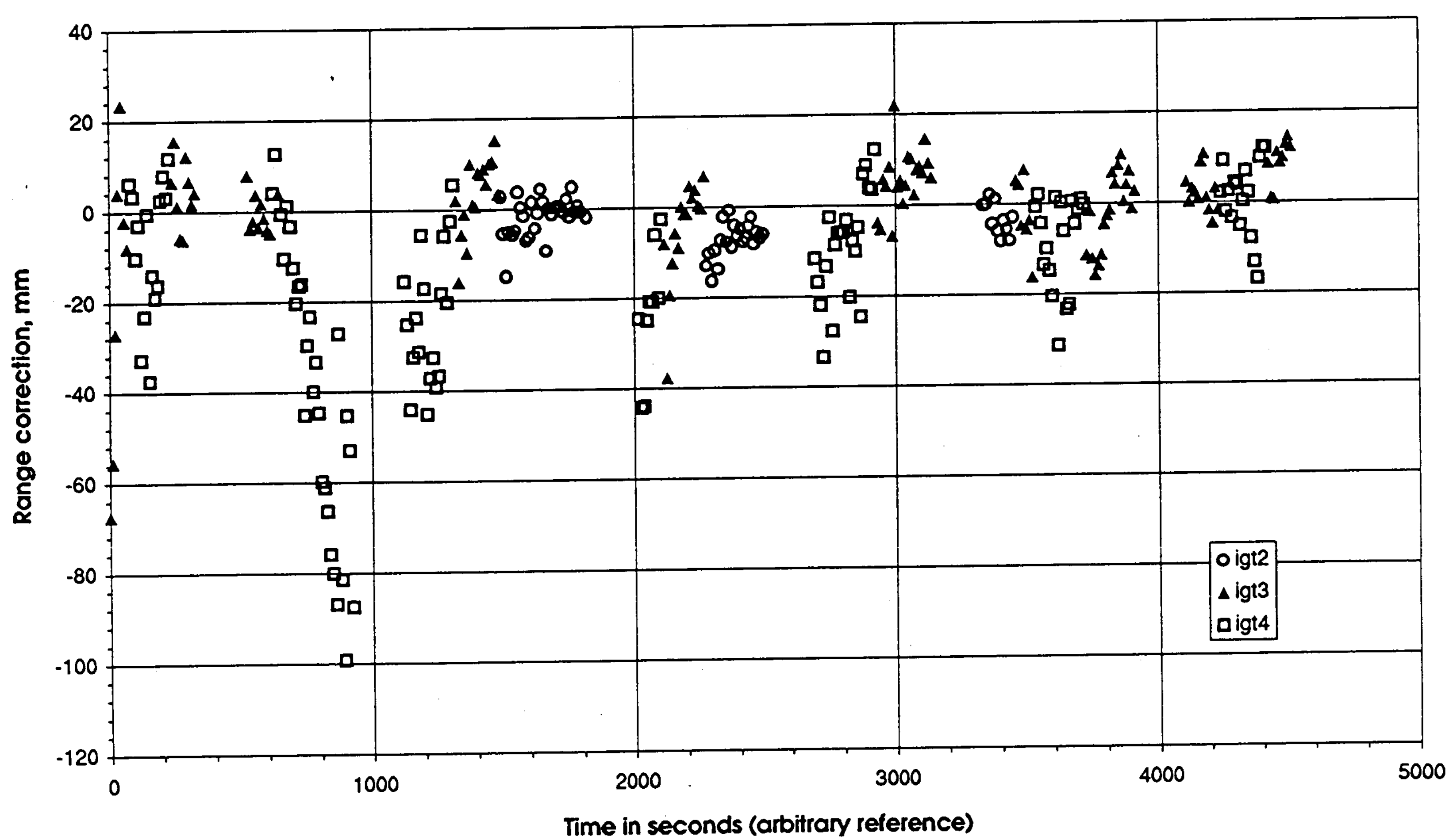
SWH estimate, m
Time in seconds (arbitrary reference)
igt2
igt3
igt4
0
2
4
6
8
10
12
14
0
1000
2000
3000
4000
5000

Fig. 9b



Attitude estimate, degrees
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
1000
2000
3000
4000
5000
Time in seconds (arbitrary reference)
indgt2
indgt3
indgt4

Fig. 10a



Range correction, mm
40
20
0
-20
-40
-60
-80
-100
-120
0
1000
2000
3000
4000
5000
Time in seconds (arbitrary reference)
igt2
igt3
igt4

Fig. 10b

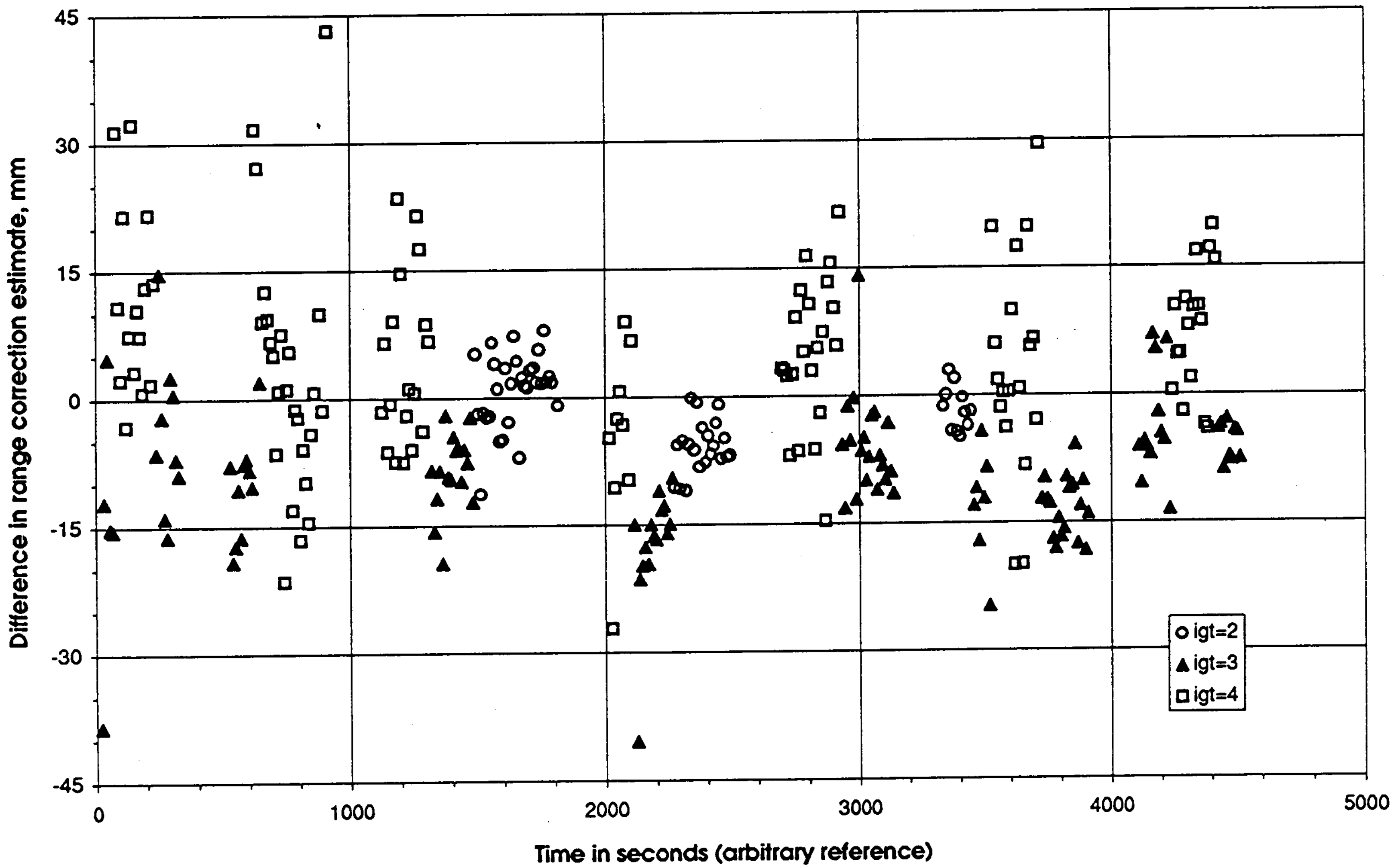
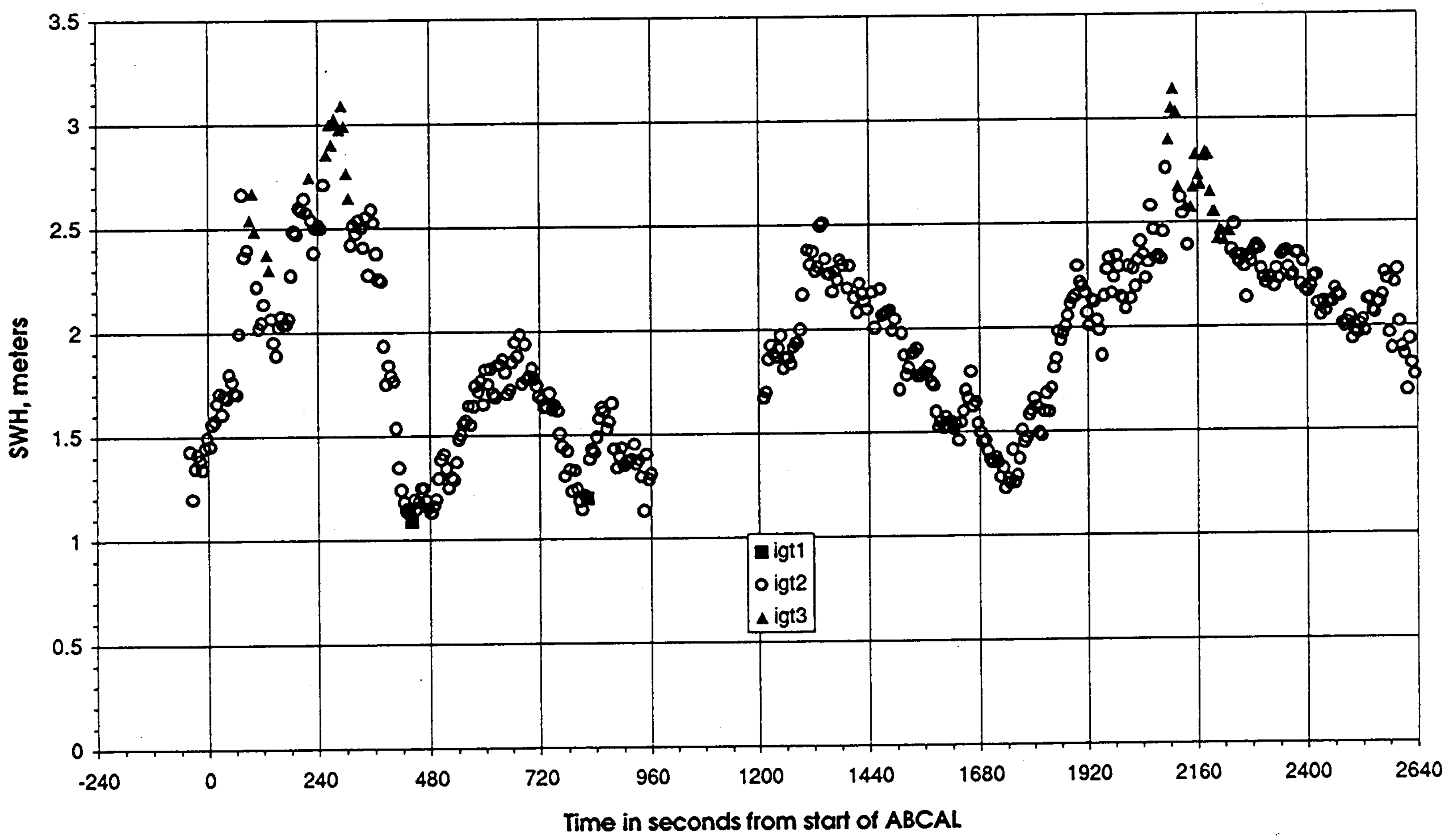
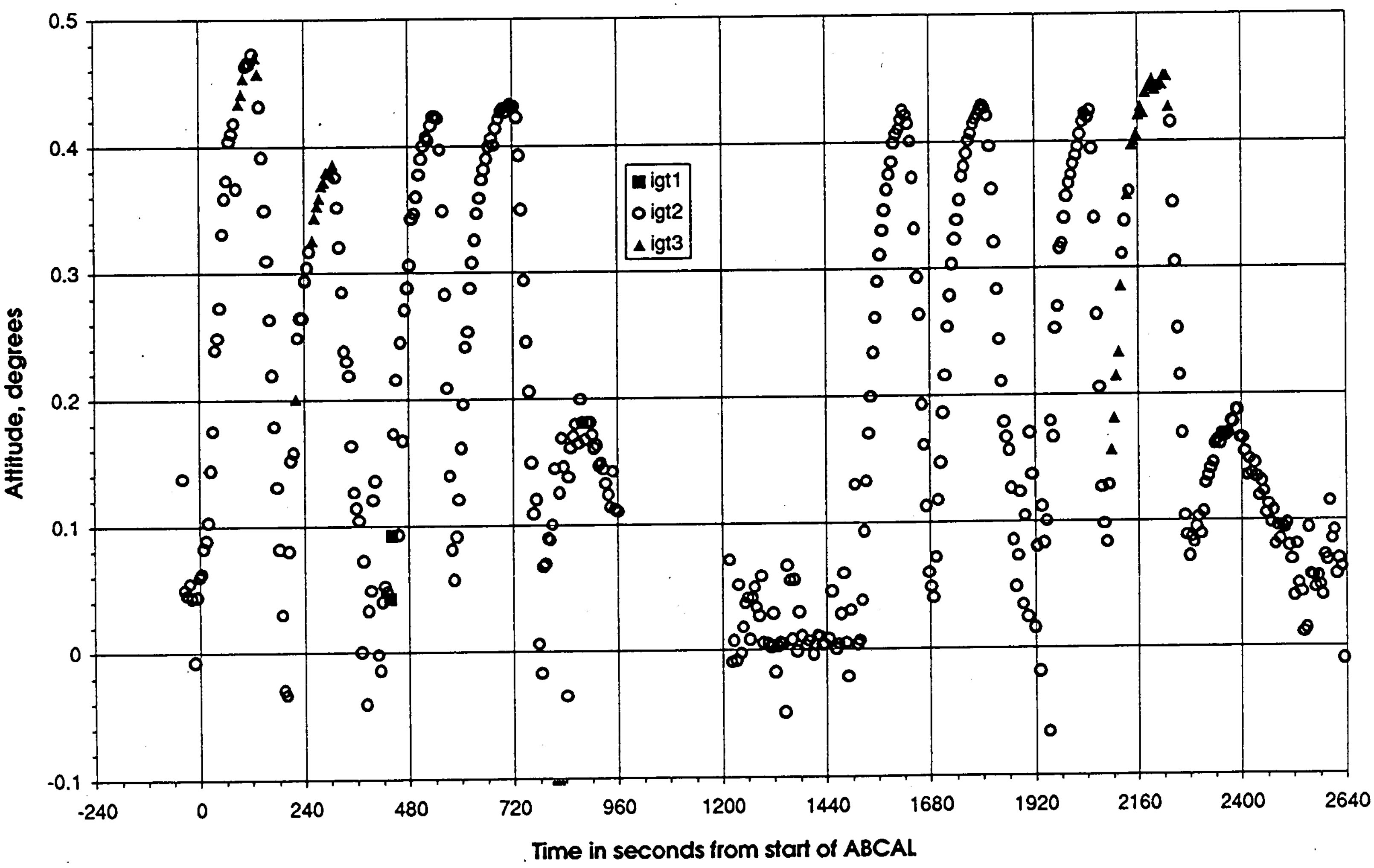

Difference in range correction estimate, mm
45
30
15
0
-15
-30
-45
0
1000
2000
3000
4000
5000
Time in seconds (arbitrary reference)
igt=2
igt=3
igt=4

Fig. 11a



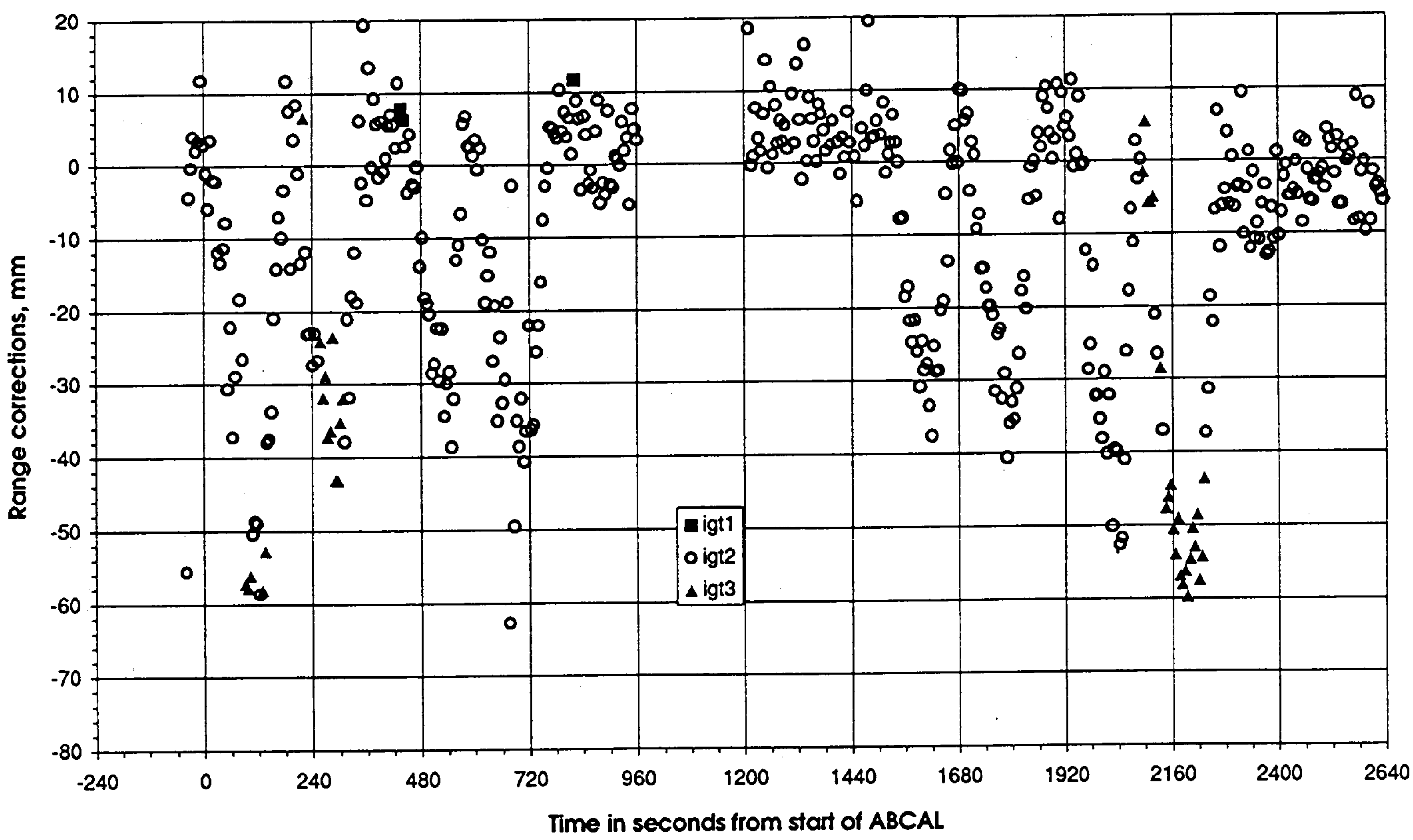
3.5
3
2.5
2
1.5
1
0.5
0
SWH, meters
-240
0
240
480
720
960
1200
1440
1680
1920
2160
2400
2640
Time in seconds from start of ABCAL
igt1
igt2
igt3

Fig 11b.



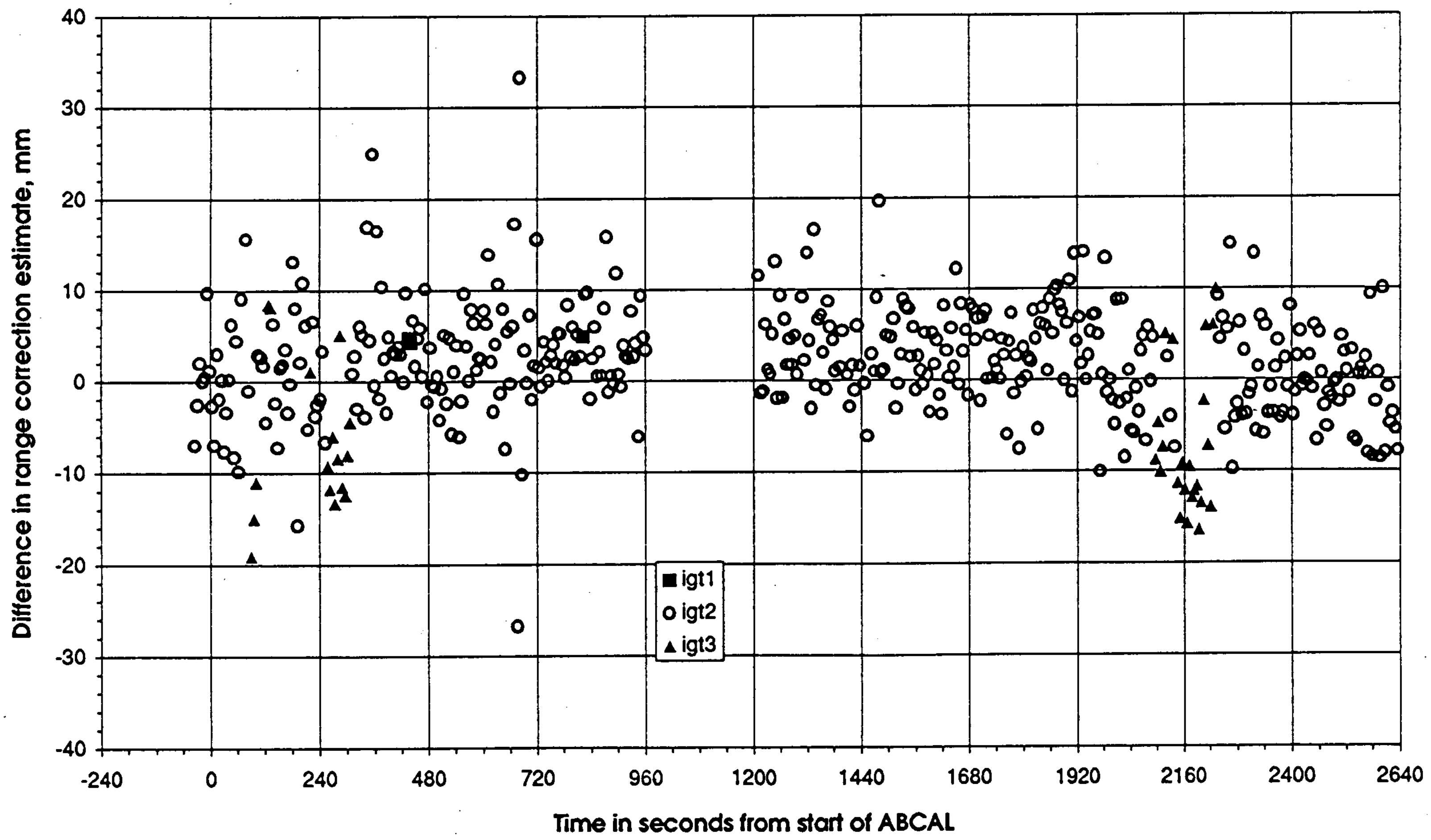
Attitude, degrees
0.5
0.4
0.3
0.2
0.1
0
-0.1
igt1
igt2
igt3
-240
0
240
480
720
960
1200
1440
1680
1920
2160
2400
2640
Time in seconds from start of ABCAL

Fig. 12a



Range corrections, mm
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-240
0
240
480
720
960
1200
1440
1680
1920
2160
2400
2640
Time in seconds from start of ABCAL
igt1
igt2
igt3

Fig. 12b



Difference in range correction estimate, mm
40
30
20
10
0
-10
-20
-30
-40
-240
0
240
480
720
960
1200
1440
1680
1920
2160
2400
2640
Time in seconds from start of ABCAL
igt1
igt2
igt3